Politechnic University of Catalonia

Doctoral Thesis

Modeling strategies for volcanic ash dispersal and management of impacts on civil aviation

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Declaration of Authorship

I, Chiara Scaini, declare that this thesis titled 'Modeling strategies for volcanic ash dispersal and management of impacts on civil aviation' and the work presented in it are my own. I confirm that:

- This work was done while in candidature for a research degree at this University.
- Where any part of this thesis has previously been submitted for a degree or any other qualification at this University or any other institution, this has been clearly stated.
- Where I have consulted the published work of others, this is always clearly attributed.
- Where I have quoted from the work of others, the source is always given. With the exception of such quotations, this thesis is entirely my own work.
- I have acknowledged all main sources of help.
- Where the thesis is based on work done by myself jointly with others, I have made clear exactly what was done by others and what I have contributed myself.

Signed: ______________________________

Date: ______________________________

"On ne découvre pas de terre nouvelle sans consentir à perdre de vue, d'abord et longtemps, tout rivage"

André Gide

A Teresa, le mie profonde radici,

ai miei genitori, robusto tronco, linfa vitale

a mia sorella Anna, brezza leggera, verdi germogli
e a Jose, il mio cielo azzurro.

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POLYTECHNIC UNIVERSITY OF CATALONIA

Abstract

Faculty of Environmental Engineering
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Doctor of Science

Modeling strategies for volcanic ash dispersal and management of impacts on civil aviation

by Chiara Scaini

During April-May 2010, the eruption of Eyjafjallajökull volcano in Iceland caused the largest breakdown of civil aviation after World War II. Although the eruption was weak in intensity, the dispersal of volcanic ash clouds over northern and central Europe resulted in more than 100.000 flights canceled and caused over USD 1.7 billion economical losses. This event and its unexpected effects raised many questions amongst the affected communities and stakeholders. But were these impacts totally unexpected? What could have been done to improve preparedness of aviation sector? The harmful effects of volcanic ash on aircraft's components have long been recognized, and ash dispersal patterns in the atmosphere can be forecasted thanks to sophisticated numerical models. However, the Eyjafjallajökull eruption revealed a low preparedness of society to direct and indirect impacts of volcanic eruptions and pointed out some flaws that must be improved for a better air traffic management. The issues pointed out by the 2010 crisis are the starting point of this PhD research, which aims at improving aviation management in case of volcanic eruptions. This manuscript describes the novel contributions developed during a 4-year period of research. Tephra dispersal modeling strategies have been enhanced and focused on civil aviation purposes. In addition, this research proposes a novel approach to assess vulnerability of the air traffic network and its element. Contributions of this research have been applied to case-studies and specific results have been published in a collection of journal papers. This PhD research provides useful insights to reduce impacts of volcanic eruptions on civil aviation and, eventually, on the whole society. Results are discussed from a wider point of view, identifying further work to be done in this rapidly evolving field.

Abbreviations

ACI	**A**irport **C**ouncil **I**nternational
ADS	**A**dvection **D**iffusion **S**edimentation
ATFM	**A**ir **T**raffic **F**low **M**anagement
ATM	**A**ir **T**raffic **M**anagement
BSC-CNS	**B**arcelona **S**upercomputing **C**enter - **C**entro **N**acional de **S**upercomputación
BPT	**B**uoyant **P**lume **T**heory
CAA	**C**ivil **A**viation **A**uthority, United Kingdom
CDF	**C**umulative **D**istribution **F**unction
DBMS	**D**ataBase **M**anagement **S**ystem
DDR	**D**emand **D**ata **R**epository
DSS	**D**ecision **S**upport **S**ystem
EASA	**E**uropean **A**viation **S**ecurity **A**gency
ECMWF	**E**uropean **C**enter for **M**edium-Range **W**eather **F**orecasts
ERS	**E**ruption **R**ange **S**cenario
ESP	**E**ruption **S**ource **P**arameters
EVITA	**E**uropean Crisis **V**isualization **I**nteractive **T**ool for **A**TFM
FIR	**F**light **I**nformation **R**egions
FL	**F**light **L**evel
FS	**F**ilkenstein - **S**chafer method
GDAL	**G**eospatial **D**ata **A**bstraction **L**ibrary
GIS	**G**eographical **I**nformation **S**ystem
GRASS	**G**eographic **R**esources **A**nalysis **S**upport **S**ystem
HDF5	**H**ierarchical **D**ata **F**ormat **5**
IATA	**I**nternational **A**ir **T**ransport **A**ssociation
IAVW	**I**nternational **A**irways **V**olcano **W**atch

ICAO	**I**nternational **C**ivil **A**viation **O**rganization
ID	**ID**entifier
IFALPA	**I**nternational **F**ederation of **A**ir **L**ine **P**ilots **A**ssociation
INETER	**I**nstituto **N**icaraguense para **E**studios **TER**ritoriales, Nicaragua
INGV	**I**stituto **N**azionale di **G**eofisica e **V**ulcanologia, Italy
IS	**I**nformation **S**ystem
IUGG	**I**nternational **U**nion of **G**eodesy and **G**eophysics
IVATF	**I**nternational **V**olcanic **A**sh **T**ask **F**orce
LLERS	**L**ong **L**asting **E**ruptive **R**ange **S**cenario
LLOES	**L**ong **L**asting **O**ne **E**ruption **S**cenario
MER	**M**ass **E**ruption **R**ate
MMS	**M**edium **M**agnitude **S**cenario
NCAR	**N**ational **C**enter for **A**tmospheric **R**esearch
NCEP	**N**ational **C**enters for **E**nvironmental **P**rediction
NetCDF	**Net**work **C**ommon **D**ata **F**orm
NOTAM	**NO**tice **T**o **A**ir**M**en
NUTS	**N**omenclature of **T**erritorial **U**nits for **S**tatistics
NWPM	**N**umerical **W**eather **P**rediction **M**odel
NOP	**N**etwork **O**peration **P**ortal
OES	**O**ne **E**ruption **S**cenario
PDF	**P**robability **D**ensity **F**unction
QGIS	**Q**uantum **G**eographical **I**nformation **S**ystem
RMSD	**R**oot **M**ean **S**quare **D**ifference
SAAM	**S**ystem for traffic **A**ssignment and **A**nalysis at a **M**acroscopic level
SQL	**S**upported **Q**uery **L**anguage
SESAR	**S**ingle **E**uropean **S**ky
SIGMET	**SIG**nificant **MET**eorological Information
SRA	**S**afety **R**isk **A**ssessment
TGSD	**T**otal **G**rain **S**ize **D**istribution
TMY	**T**ypical **M**eteorological **Y**ear
TTDM	**T**ephra **T**ransport and **D**ispersal **M**odel
UTC	**C**oordinated **U**niversal **T**ime
USGS	**U**nited **S**tates **G**eological **S**urvey

UTM	**U**niversal **T**ransverse **M**ercator
USDA	**U**nited **S**tates **D**epartment of **A**griculture
VAAC	**V**olcanic **A**sh **A**dvisory **C**enter
VALS	**V**olcano **A**lert **L**evel **S**ystem
VAST	**V**olcanic **A**sh **S**trategic Initiative **T**eam
VATDM	**V**olcanic **A**sh **T**ransport and **D**ispersal **M**odel
VEI	**V**olcanic **E**xplosivity **I**ndex
VOLCEX	**VOLC**anic ash **EX**ercise
WMSD	**W**eighted **M**ean **S**quare **D**ifference
WRF	**W**eather **R**esearch and **F**orecasting **M**odel
WF	**W**eighted **F**actor
WMO	**W**orld **M**eteorological **O**rganization

Chapter 1

Introduction

1.1 Background

During April-May 2010 the eruption of Eyjafjallajökull volcano in Iceland caused the largest breakdown of civil aviation after World War II (Oxford Economics, 2010). Although the eruption was weak in intensity, the dispersal of volcanic ash clouds over northern and central Europe resulted in more than 100.000 flights canceled and caused over USD 1.7 billion economical losses (IATA Economics, 2010). One year later, the eruption of Cordón Caulle volcano in Chile caused large-scale disruption of air traffic operations across the southern hemisphere, with hundreds of flight cancellations in Australia and New Zealand. But how can volcanic eruptions cause severe disruptions at continental scales? Were these impacts totally unexpected? What could be done to improve preparedness of aviation sector and reduce societal impacts of air traffic disruptions?

The harmful effects of volcanic ash on aircraft's fuselage, turbines and navigation instruments have long been recognized, especially after the famous British Airways Flight 9, impacted by Mt. Galunggung's volcanic ash in 1982 (the "Djakarta incident"). Since then, more than 100 aircraft encounters with ash clouds have been officially documented (Guffanti et al., 2008). Given the threat posed by volcanic ash clouds on flight safety, the International Civil Aviation Organization (ICAO) established in 1994 the International Airways Volcano Watch (IAVW) program to provide international arrangements for the monitoring of volcanic ash in the atmosphere and warnings to the aviation community. Moreover, Volcanic Ash Advisory Centers (VAACs) were constituted in 1997 and are

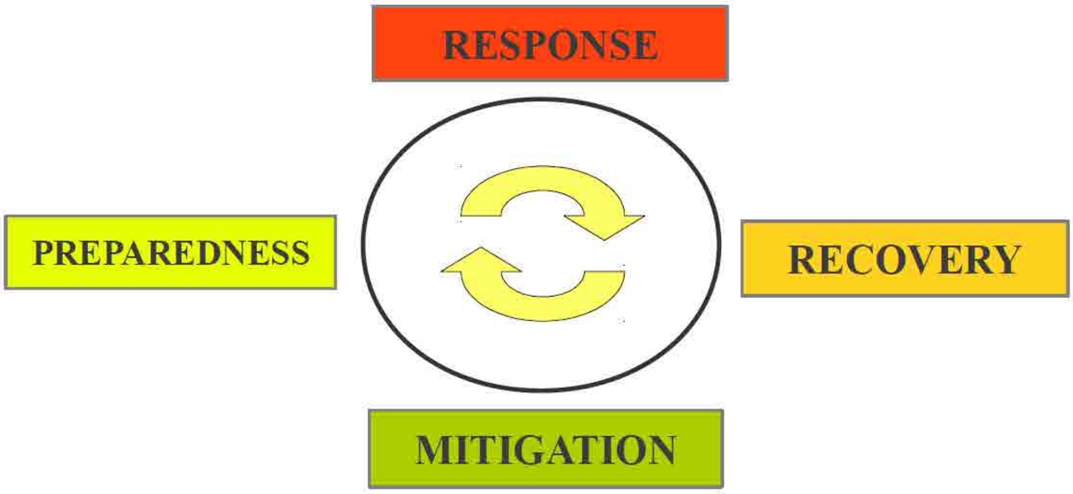

Figure 1.1: Disaster management cycle constituted by 4 phases: response, recovery, mitigation and preparedness.

officially designed by the IAVW for issuing volcanic ash warnings and forecasts. But the procedures to be implemented in case of ash-contaminated airspace where never applied before in dense air traffic network such as the European, and perception of volcanic risk amongst many involved stakeholders remained low until the 2010 event. At the same time, the continuous increasing demand of passenger's air transportation makes air traffic network management more challenging. All these factors contributed in increasing the vulnerability of stakeholders involved in aviation management during volcanic eruptions, in particular in Europe. Thus, after the 2010 events, the attention of aviation sector on risk management procedures in case of explosive volcanic eruptions increased dramatically.

In general, risk analyses distinguish between two timescales: short-term emergency management and long-term planning, following a general scheme called "disaster management cycle" (Vasilescu et al., 2008; Khan, 2008; Joyce et al., 2009). The fist phase of the cycle is constituted by the immediate response, the implementation of emergency plans and the societal recovery. The second part of the cycle consists in the definition of mitigation measures and the preparedness phase. The ultimate goal is to increase resilience and reduce future impacts. Short-term timescale corresponds to the emergency phase, when response strategies are implemented, while long-term refers to territorial planning and other activities aimed at increasing preparedness. The general scheme (Fig. 1.1) is maintained, with some modifications, in all branches of risk management, and amongst them in volcanic risk management (De la Cruz-Reyna and Tilling, 2008).

In particular, volcanic risk management has been traditionally focused on the mitigation and reduction of direct impacts on population (e.g. pyroclastic density currents, Zuccaro et al., 2008), which are given a higher priority by governments and public stakeholders, due to their strong social impact. However, indirect impacts of explosive eruptions, for example due to the disruption of infrastructures (e.g. roads, communications) contribute to a substantial portion of socio-economic impacts of volcanic events (Spence et al., 2006). In the specific case of volcanic ash dispersal, the disruption of air traffic is relevant from both points of view: the direct damage of aircraft's components can cause casualties to crew and passengers, and the disruption of air traffic operations can impact a much wider area than the one directly affected by ash dispersal. Finally, the indirect impacts can potentially affect the socio-economic system at global scale, due to the strong interdependencies between air traffic services and commercial activities (e.g. import/export).
At both short and long-term, Tephra [1] Transport and Dispersal Models (TTDMs; Folch, 2012), a type of atmospheric dispersion models, are the main instrument used to support decision-makers and provide relevant information on ash dispersal patterns in atmosphere. Their usage is often associated to meteorological models and to a network of monitoring and alert sytems. On one hand, short-term (hours to days) emergency management of volcanic crises are based on forecast maps. Before 2010, the delivered forecast product was of qualitative nature and the criterion for airspace closure was based on a "zero ash tolerance", applied during the first days of the Eyjafjallajökull eruption. Quantitative concentration thresholds where then adopted in Europe, being at present (December 2014) still under discussion within the wide range of involved stakeholders. Fig. 1.2 shows an example of volcanic ash dispersal forecasts issued by London VAAC during the Eyjafjallajökull eruption (left) and quantitative ash concentration charts issued by U.K. meteorological office during the 2011 Grímsvötn eruption. Before 2010, operational TTDMs were used mainly on a qualitative basis, the adoption of quantitative criteria found the institutions in charge of ash forecast unprepared, and the operational set up of models had to be adapted on-the-fly. At present, although VAACs are not

[1] Tephra is the general term for the fragmented material ejected during an explosive volcanic eruption, regardless of its size and composition. The term ash refers only the finest fraction of tephra, i.e. particles smaller than 2 mm in diameter. In principle, TTDMs can be used to model the atmospheric transport of ejected material from few cm to few μm in diameter. Models that focus only on the fine fraction (i.e. ash and fine ash) are also known as Volcanic Ash Transport and Dispersal Models (VATDMs), but this distinction is not relevant here.

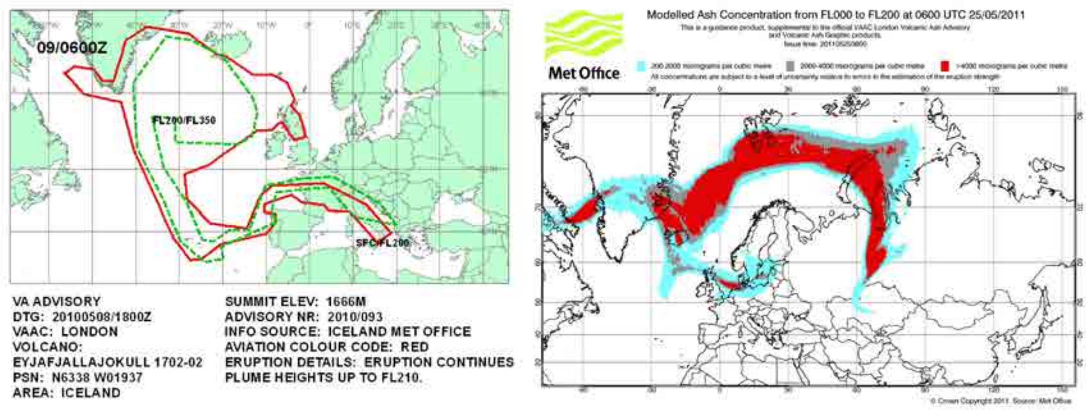

FIGURE 1.2: Evolution of volcanic ash charts during the 2010 crisis. The first ash forecasts were qualitative (left), with maps showing the contours delimiting the volcanic ash cloud at three different flight levels. After the introduction of quantitative thresholds (right) ash charts were issued separately for each flight level showing concentration contours for three thresholds of 0.2 2 and 4 mg/m^3.

officially required by ICAO to produce short-term quantitative maps of ash concentration, some of them (e.g. London and Tolouse VAACs) issue complementary quantitative products. In addition, other institutions (e.g. research centers or volcano observatories) run operational forecasts and issue both official and unofficial products, often used by aviation stakeholders (VAST2012). On the other hand, the interest in long-term impacts on civil aviation is increasing, as volcanic ash contamination is being included in Safety Risk Assessment (SRA) procedures that allow operations in ash-contaminated airspace. TTDMs can support these analysis by producing long-term probabilistic hazard maps that give the probability for a critical ash concentration value to be exceeded at each point of the computational domain. Until 2010, hazard maps existed only for tephra fallout and not for airborne concentration, partly because the generation of quantitative ash concentration maps requires numerical models with higher computational cost. The 2010 Eyjafjallajökull crisis triggered a deep change in aviation procedures in case of ash-contaminated airspace, in particular in Europe. This event revealed some flaws that must be improved for a better crisis management, from both the point of view of the scientific community (volcanologists, atmospheric modelers) and the aviation stakeholders (aviation managers and operators). Since 2010, the scientific community has been constantly improving TTDMs (Folch, 2012; Bonadonna et al., 2011a; Bonadonna et al., 2013). The first IUGG-WMO (International Union of Geodesy and Geophysics - World meteorological Organization) Ash Dispersal Forecast and Civil Aviation Workshop (Bonadonna et al., 2011b) gathered more than 50 scientists from 12 countries to compare different TTDMs and discuss the short-term scientific road-map. Since 2010, aviation stakeholders have been applying new procedures in case of ash-contaminated airspace such as SRA (ICAO, 2012a) and exercises for improving emergency management (Bolić and Sivčev, 2012). All these meetings and activities pointed out the key aspects to be developed from both scientific and aviation point of view. In addition, and from both sides, the 2010 crisis pointed out the low efficiency of information flow: scientists and aviation stakeholders had to deal with an information overload that increased the reaction times, and some of the volcanic ash alert procedures were found to be redundant. Collaboration between aviation stakeholders and scientists has been strongly enhanced in last years and led to an overall improvement of the coping capacity during volcanic eruptions, but there is still a need for improving multidisciplinary collaborations and projects between scientific and aviation communities (Bonadonna et al., 2013). Needs expressed by each stakeholder can be synthesized as follows:

For the scientific community (atmospheric transport modelers, volcanologists):

- Improve some aspects of TTDMs physics
- Improve of TTDM modeling strategies
- Improve the definition of the Eruption Source Parameters (ESPs) for TTDMs
- Enhancement of monitoring techniques at both short and long-term
- Quantify uncertainties associated with the forecasting process
- Produce forecasts and hazard maps focused on civil aviation needs

For aviation stakeholders (VAACs, airport authorities, airlines), risk managers, decision makers and territorial planners:

- Speed up procedures
- Avoid information overload
- Improve information exchange
- Quantification of the vulnerability of the air traffic system to volcanic eruptions
- Estimate expected impacts on air traffic system
- Improve emergency management and define mitigation strategies

- Produce and apply SRAs in case of ash-contaminated airspace
- Produce long-term risk management plans for volcanic risk to aviation
- Reduce socio-economic impacts at both short and long-term

This research aims at addressing part of these needs, in particular those related to the creation of an integrated risk management strategy between the stakeholders.

1.2 Objectives of the Thesis

The research activity is supported by the Spanish national research project ATMOST (Atmospheric Transport Models and Massive Parallelism, CGL2009-10244). The project is focused on modeling dispersal of volcanic ash at regional scale and pollutants at an urban microscale. This thesis develops one of the topics of the project (i.e. ash dispersal modeling in atmosphere), focusing on civil aviation needs. The main objective is to support air traffic management during explosive volcanic eruptions.
Impacts of volcanic ash dispersal on aviation do not only depend on expected hazardous conditions (i.e. presence and concentration of volcanic ash), but rely also on the vulnerability of the exposed targets (i.e., the air traffic network and its elements). Thus, given that risk management builds on hazard, vulnerability and impact assessment, the research field was enlarged in order to include these three main concepts.
Although the strong multidisciplinary character of this topic, analyses are usually performed separately by different groups of stakeholders (i.e., volcanological community and aviation managers, respectively). In addition, different stakeholders make use of very different tools, often adapted from a much more general purpose, and very few tools developed for air traffic management in cases of ash-contaminated airspace are currently available. Finally, this work follows the timescale distinction traditionally applied in risk

TABLE 1.1: Main objectives of the PhD thesis

	SHORT-TERM	LONG-TERM
Hazard	Ash dispersal forecast	Hazard assessment
Vulnerability/Impact	Response/mitigation	planning/preparedness

management, and analyses two timescales: long-term, intended as the scale at which territorial planning is implemented and focused on preparedness, and short-term, mainly focused on emergency and response (Fig. 1.1). The research presented here follows this distinction and contributes to existing strategies for TTDM and vulnerability/impact assessment at long and short-term timescales (Table 1.1).
The aims of the research are:

- Improve some aspects of short and long-term volcanic **ash dispersal modeling strategies** (aimed at producing, respectively, forecasts and hazard maps)
- Propose a novel approach to assess **vulnerability and impacts** on air traffic network its elements
- Develop a **map-based tool** to estimate impacts of volcanic ash dispersal on air traffic system and support air traffic management during volcanic crises. In particular, the intention is to use Geographical Information Systems (GIS) at its full potential, to enhance the current vulnerability impact assessment methodologies

A seconday objective is to contribute to the improvement of communication between stakeholders, a critical issue underlined during and after the 2010 aviation crisis (Bonadonna et al., 2011a; Bolić and Sivčev, 2012; Bonadonna et al., 2013).

1.3 Structure of this document

This document resumes the work done during the 4-years research activity. It is constituted by a compendium of publications (Appendix A). The text covers the relevant topics of the research and complements the information providing a general background, that allows appreciating the research work as a whole. Also, specific information on the methodology and results of complementary analyses are added when not fully described in the papers. The document is organized as follows:

- Chapter 2 presents the state-of-the-art for each main topic considered during the PhD study. The review poses the basis for the definition of specific objectives, focused at filling current gaps in knowledge and methodologies.

- Chapter 3 describes novel contributions and the methodologies proposed, that have been applied to case-studies (Concepción volcano, Nicaragua; Popocatépetl volcano, Mexico; Vesuvius volcano, Italy; 4 Icelandic volcanoes, Iceland)).
- Chapter 4 presents the main findings of this research and discusses results
- Chapter 5 discusses implications from a wider point of view, identifying opportunities for future work.

The methodologies introduced in this research and the results of their application have been published in a collection of journal papers (attached to this document), some of them included in the compendium of publications.

1.4 List of publications for the compendium

- **Paper I**: **Scaini, C.**, Folch, A., Navarro, M.. "Tephra hazard assessment at Concepción volcano, Nicaragua", Journal of Volcanology and Geothermal Research (**IF 2.515, 5-years IF 2.664**), vol. 219-220, pp. 41-51, 2012.
- **Paper II**: Bonasia, R., **Scaini, C.**, Capra, L., Nathenson, M., Araña Salinas, L., Siebe, C., Folch, A.. "Long-range hazard assessment of volcanic ash dispersal for a Plinian eruptive scenario at Popocatépetl volcano (Mexico): implications for civil aviation safety", Bulletin of Volcanology (**IF 2.667**), 76, 789, 2013.
- **Paper III**: **Scaini, C.**, Biass, S., Galderisi, A., Bonadonna, C., Folch, A., Smith, K. and Höskuldsson, A.. "A multi-scale risk assessment for tephra fallout and airborne concentration from multiple Icelandic volcanoes - Part II: vulnerability and impact", Nat. Hazards Earth Syst. Sci. (**IF 1.826, 5-years IF 2.075**), 14, 2289–2312, 2014, www.nat-hazards-earth-syst-sci.net/14/2289/2014/doi:10.5194/nhess-14-2289-2014
- **Paper IV**: **Scaini, C.**, Folch, A., Bolić, T., Castelli, L.. "A GIS-based tool to support air traffic management during explosive volcanic eruptions", Transportation Research Part C: Emerging Technologies (**IF 2.820, 5-years IF 3.118**), pp. 19-31, 10.1016/j.trc.2014.09.020.

Other publications have been produced during the PhD and are not included in the compendium. These works are referenced in the text and the accepted publications are included in Appendix B. In particular, the work presented in **Paper III** is based on a companion paper that contains relevant information for the understanding of the second part. Given the relevant contribution given to this work, and that the paper is published with open access, the full text is attached in Appendix B.

- **Sulpizio et al,. 2012**: Sulpizio, R., Folch, A., Costa, A., **Scaini, C.**, Dellino, P. "Hazard assessment of far-range volcanic ash dispersal from a violent Strombolian eruption at Somma-Vesuvius volcano, Naples, Italy: implications on civil aviation." Bulletin of Volcanology (**IF 2.667**), DOI 10.1007/s00445-012-0656-3, 2012.

- **Scaini et al., 2012**: **Scaini, C.**, A. Folch, "The role of GIS in multi-scale impact assessment of explosive volcanic eruptions: case-study of Concepción volcano, Nicaragua.", proceedings of the 21st GIS Research UK (GISRUK) conference, School of Environmental Sciences, University of Liverpool, 3-5 April 2012. Paper awarded with the "best Early Career Research" Award.

- **Scaini et al., 2013**: **Scaini, C.**, T. Bolić, L. Castelli, A. Folch. "GIS-based tool for the estimation of impacts of volcanic ash dispersal on European air traffic", Schaefer, Dirk (Editor), Proceedings of the 3rd SESAR Innovation Days (2013) EUROCONTROL. ISBN ISBN 978-2-87497-074-0.

- **Biass et al., 2014**: Biass, S., **Scaini, C.**, Bonadonna, C., Folch, A., Smith, K., Höskuldsson, A.. "A multi-scale risk assessment for tephra fallout and airborne concentration from multiple Icelandic volcanoes - Part I: Hazard assessment", Nat. Hazards Earth Syst. Sci. (**IF 1.826, 5-years IF 2.075**), 14, 2265–2287, 2014. www.nat-hazards-earth-syst-sci.net/14/2265/2014/ doi:10.5194/nhess-14-2265-2014.

- **Scaini et al., submitted**: **Scaini, C.**, T. Bolić, A. Folch, L. Castelli, "Civil aviation management during explosive volcanic eruptions: a survey on the stakeholders' perspective", Journal of Volcanology and Geothermal Research (**IF 2.515, 5-years IF 2.664**), submitted.

Chapter 2

State-of-the-art and specific objectives

2.1 Tephra hazard modeling strategies

This section overviews the state-of-the art of existing tephra hazard modeling strategies at both short and long-term, and identifies cutting-edge developments and open issues. Specific objectives of this research are defined based on this overview, and address some aspects to be improved in current tephra hazard modeling.

2.1.1 State-of-the-art of tephra hazard modeling strategies

2.1.1.1 Tephra Transport and Dispersal Models

Tephra Transport and Dispersal Models (TTDMs) are Atmospheric Transport Models (ATMs) used to simulate tephra dispersal in atmosphere. TTDMs are often referred as Volcanic Ash Transport and Dispersal Models (VATDMs), which are actually a subgroup of TTDMs especially adapted to model volcanic ash.

TTDMs can be classified as Eulerian or Lagrangian models. The main difference is that Eulerian models use a fixed three-dimensional grid (typically Cartesian), whereas Lagrangian models calculate the trajectories of "particles" within the computational domain. Hybrid Eulerian-Lagrangian approaches are also possible. Eulerian models can be classified depending on how the mass transport or Advection-Diffusion-Sedimentation

(ADS) equation is solved. Gaussian models (also called "Semi-analytical") consider a simplified ADS equation (Costa et al., 2006) and obtain an analytical solution under strong assumptions (homogeneous and steady wind field, Macedonio et al., 2005). Examples of such models are TEPHRA2 (Bonadonna et al., 2005) and HAZMAP (Macedonio et al., 2005). Gaussian models calculate the total mass deposited at ground and, because admit analytical solutions, require lower computational resources (Folch and Sulpizio, 2010). However, the calculation of ash concentration (Folch, 2012) requires a fully numerical approach in order to solve the complete ADS equation. An example of fully numerical model is FALL3D (Costa et al., 2006; Folch et al., 2009), an Eulerian TTDM developed at the Italian Istituto Nazionale di Geofisica e Vulcanologia (INGV) and the Barcelona Supercomputing Center (BSC). A detailed review of TTDM models has been performed by Folch (2012), and its main characteristics are summarized in the Consensual document from the 1st Ash Dispersal Forecast and Civil Aviation Workshop (Bonadonna et al., 2011a). Folch (2012) underlines the range of application and the characteristics of existing models presenting a comparative table (Table 2.1).

TTDMs differ in many aspects, and in particular in the definition and/or modeling of the source term, that is, the eruptive column and its characteristics ("source term", bottom line of Table 2.1). The vertical distribution of mass along the eruptive column can be modeled as uniform, linear or parametric (Suzuki, 1983), or applying 1D Buoyant Plume Theory models (BPT, Bursik, 2001) that account for column-wind interaction. There are also more complex source models, which take into account wind interaction and the 3D structure of the plume (Neri et al., 2007; Suzuki and Koyaguchi, 2013) but have a higher computational cost. The modeling of weak plumes and wind-plume interaction is still an open issue (Folch, 2012) and the interaction of wind with eruptive column is an important factor in assessing potential impact of a given scenario on air traffic (Bursik et al., 2009). Inputs of TTDM are commonly divided in two groups: meteorological and volcanological inputs.

- Meteorological inputs. Meteorological data are the driver for running the TTDM. They can be stored in many different formats and contain simple vertical wind profiles (for Gaussian TTDMs) or 4D gridded variables (for numeric TTDMs).

- Volcanological inputs of a TTDM are the Eruption Source Parameters (ESP) that include column height, eruption duration, erupted mass and characteristics of the ejected material. An overview of the techniques used for the determination of ESPs

	ASH3D	ATHAM	FALL3D	FLEXPART	HYSPLIT	JMA-GATM JMA-RATM	MLDP0	MOCAGE	NAME	PUFF	TEPHRA2	VOL-CALPUFF
Operational	■		■	■	■	■	■	■	■	■	■	■
Approach (1)	E/H	E	E	L	H	L	L	E	LH	L	E	H
Method (2)	N	N	N	N	N	N	N	N	N	N	A	S
Coverage (3)	LRG	L	LR	LRG	LRG	RG	LRG	G	LRG	LRG	L	LR
Physics												
Topography	■	■	■	■	■	■	■	■	■	■	■	■
H wind advection	■	■	■	■	■	■	■	■	■	■	■	■
V wind advection	■	■	■	■	■	■	■	■	■	■		■
H atm. diffusion	■	■	■	■	■	■	■	See (5)	■	■	■	■
V atm. diffusion	■	■	■	■	■	■	■	■	■	■		■
Particle sed.	■	■	■	■	■	■	■	■	■	■	■	■
Other dry dep.			■	■	■		■	■	■			
Wet deposition	■	■	■	■	■	■	■	■	■			■
Dry part. aggregation												
Wet part. aggregation			■									
Variable part. shape	■		■		■	■	■					■
Gas species		■	■	■	■			■	■			■
Chemic. processes				■	■				■			■
Granulometry												
Variable size class.	■	■	■	■	■		■	■	■	■	■	■
Variable GS distr.	■		■	■	■				■		■	■
Variable size limits	■	■	■	■			■		■	■	■	■
Source term												
Mass distribution (4)	PS/U/ LN	O	ALL	PS/L/U/P/O	PS/L/U/P/LN	PS/L/LN	PS/L/U/P/O	PS/L	PS/L/U/BP/ O	PS/L/U/P /O	L/U/LN/O	PS/BP

(1) L=Lagrangian, E=Eulerian, H=Hybrid
(2) A=Analytical, S=Semi-analytical, N=Numerical
(3) L=Local, R=Regional, G=Global
(4) PS=Point Source, L=Linear, U=Umbrella-type, P=Poisson, LN=Log-normal, BP=Buoyant Plume, O= Other (see Model Summary Document).
(5) Neglected. Diffusion of numerical origin appears to be sufficient, with particularly good results at 0.5°.

TABLE 2.1: Comparison of existing TTDMs (from IUGG-WMO, 2013b. Colored/white cells indicate that the option is available/not available for the TTDM.

has been performed by Folch (2012). The Data Acquisition Document produced during the 2nd IUGG-WMO Ash Dispersal Forecast and Civil Aviation Workshop (IUGG-WMO, 2013a) synthesizes the main detection and retrieval techniques adopted for the characterization of ESPs.

Some parameters such as column height and exit velocity can be inferred by radar measurements (Gouhier and Donnadieu, 2008), infrasounds and thermal imagery (Ripepe et al., 2013). For past events, most eruptive parameters including Mass Eruption Rate (MER) are estimated a posteriori from the analysis of deposits (Carey and Sparks, 1986; Bonadonna et al., 2005) and using empirical and semi-empirical relationships (Sparks et al., 1997; Mastin et al., 2009; Woodhouse et al., 2013) or analytical expressions (Degruyter and Bonadonna, 2012).

Total Grain Size Distribution (TGSD) of ejected ash strongly influences the modeling results (Bonadonna et al., 2011c). Field studies allow reconstructing the TGSD from the analysis of deposits (e.g. Bonadonna and Houghton, 2005). However, these methods rely on the availability of complete geological records and may lead to underestimation of fine ash fraction. Recent developments are focused on quasi-real-time characterization of tephra grain size and characteristics during a volcanic event using satellite (Dean et al., 2002; Gangale et al., 2010; Kerminen et al., 2011) and ground-based measurements (Andronico et al., 2009; Marzano, 2011; Marzano et al., 2011). Finally, a critical point for the definition of the TGSD is the estimation of the percentage of aggregating particles (Costa et al., 2010), sometimes observable in the field (Bonadonna et al., 2002; Bonadonna et al., 2011a).

2.1.1.2 Tephra hazard modeling strategies

TTDMs are nowadays used by a wide range of institutions at National and International level, including research centers and private parties. These institutions run TTDMs under different configurations and employ a wide range of modeling strategies and operational configurations, depending on the requirements that are expected to fulfill. Numerical TTDMs calculate ash concentration and can simulate far-range ash dispersal but require higher computational resources (Folch and Sulpizio, 2010). The choice of the modeling strategy is not straightforward and strongly conditions the modeling results.

The main factors that contribute to the definition of modeling strategies are:

- definition of TTDM inputs
- TTDM timescale

Definition of TTDM inputs. The famous sentence "garbage in, garbage out", emphasizes the importance of a correct definition of modeling inputs. The choice of input parameters is in fact extremely relevant for the reliability of modeling results. Tephra hazard modeling strategies rely on the definition of an eruptive scenario, constituted by a set of meteorological and volcanological input parameters.

- Meteorological inputs. The type of meteorological data depends on the spatial resolution at which tephra dispersal is simulated, which in its turn depends on the specific purposes of the modeling. In fact, it is desirable that the meteorological data and the TTDM have a similar spatial resolution (Folch, 2012). If the aim is to model ash dispersal at a global scale, it is necessary to use a global Numerical Weather Prediction Model (NWPM), with resolutions ranging from 0.5° to 2.5°. For the long-term hazard assessment, is quite common to use global Reanalysis datasets such as the NCEP-NCAR Global Reanalysis dataset (Kalnay et al., 1996) or the European Center for Medium-Range Weather Forecasts (ECMWF) Era-Interim dataset. However, if the simulation is performed at local scale, it is necessary to run a mesoscale NWPM reaching higher resolutions (up to few km). The ideal strategy for interfacing meteorological and TTDM models is an on-line coupling, which allows running both contemporaneously. However, for different reasons, most TTDM use an off-line approach, in which the output of the meteorological model is used as an input for the TTDM (Folch, 2012). One of the most widely used mesoscale model is the Weather Research and Forecasting model (WRF), available in two different versions: WRF-NMM (Janjic et al., 2001) and WRF-ARW (Michalakes et al., 2001). Examples of coupling between the WRF meteorological model and the FALL3D model can be found in Folch et al. (2008) and Parra and Folch (2012).

- Volcanological inputs. The characterization of Eruption Source Parameters (ESPs) is a complex multi-disciplinary process based on geological studies, physical volcanology, and observations (Mastin et al., 2009). Column height, MER and eruption duration can be introduced as a constant value into the models, or vary according to the different measurements available. If there is no information available on the TGSD, a common method is to assume a Lognormal or bi-Lognormal distribution of the particle size (Bonadonna et al., 2005). In addition, the fraction of fine ash can be accounted in percentage. Finally, all TTDMs simplify the aggregation phenomena by changing in the initial TGSD assuming a certain aggregation percentage a priori. However, all these choices increase the uncertainty associated with modeling results, which may be partially accounted by using statistical distribution of eruptive parameters (Bonadonna et al., 2005).

TTDM timescale. Following a general distinction presented in Chapter 1, Tephra hazard modeling strategies can be classified in two different timescales (i.e. short and long-term), which correspond to two phases of risk management: response/mitigation and planning/preparedness. This distinction has been defined during the years by the modeling community (atmospheric scientists and physical volcanologists), but other communities involved in aviation management may associate timescales with different temporal ranges. Tephra hazard modeling strategies are conditioned by the temporal requirements of end-users, which may want to use modeling outcomes at different timescales (from few hours to many decades) depending on the purpose of the analysis.

- Short-term. Short-term modeling aims at forecasting the dispersal of tephra during the next few days. This is typically done by Volcanic Ash Advisory Centers, which run different TTDMs in operational mode during volcanic crises. Usually, eruptive scenarios are defined prior to the eruption in order to initialize the TTDM, and then modified when new data are available (i.e. data assimilation). In case of eruption, VAACs issue official ash dispersal forecasts every 6 hours, containing information for the following 18-24 hours, although the tendency is to increase forecast frequency (IVATF, 2011). For example, the Anchorage VAAC (Alaska) has implemented an operational forecast based on the PUFF model (Searcy et al., 1998) and monitoring (i.e. satellite remote sensing), that allows automated production of ash dispersal forecasts (Webley and Mastin, 2009). Other institutions, e.g. Volcano Observatories or National Research Centers, may also run their own operational forecast. This is the case of the Volcanological Observatory of Catania of the Italian Istituto Nazionale di Geofisica e Vulcanologia (INGV), which provides an ensemble forecast (i.e. merging results of different TTDM outputs) on a 3-hour basis (Scollo et al., 2009). But operational strategies such as the ones mentioned here have still a very low diffusion, partially due to the need for a wide range of volcanological data at quasi-real-time (often provided by monitoring networks). In addition, the demand for timely forecasts substantially increases the computational requirements. Finally, there is strong criticism on the short-term reliability of modeling outputs, that may be enhanced by the systematic adoption of techniques such as data assimilation and ensemble forecasting (Bonadonna et al., 2011a; Folch, 2012).

- Long-term. Long-term modeling aims at producing probabilistic hazard maps by merging hundreds/thousands of runs under different volcanological and meteorological conditions. Until recently, hazard maps were produced only for tephra accumulation at ground using simplified semi-analytical TTDMs (Bonadonna et al., 2005; Macedonio et al., 2008; Costa et al., 2009). The first probabilistic tephra dispersal hazard assessment computed with fully numerical models was developed by Papp et al. (Papp et al., 2005) for more than 20 active volcanoes in the Northern Pacific region, and results were merged according to the relative probability of occurrence of the considered events. First maps for airborne concentration for specific volcanoes have been produced by Folch and Sulpizio (2010) and Leadbetter and Hort (2011). However, probabilistic tephra dispersal hazard maps based on numerical simulations are still poorly diffused due to their high computational cost (Folch and Sulpizio, 2010).

  The choice of input parameters to be used for initializing TTDM for hazard assessment purposes presents specific issues. Probabilistic hazard assessment is in fact based on the choice of representative meteorological conditions for the study area. The long-term wind field characterization is extremely important for the long-term hazard assessment, as underlined in Davies et al. (2010). While semi-analytical models use vertical profiles at given points, numerical TTDM use meteorological datasets produced by meteorological models, increasing both need for storage disk space and computational cost, especially for local scale analyses when meso-scalar models are required to be run. Given that TTDMs rely on meteorological datasets and are often run at regional/global scales, the definition of such conditions based on vertical profiles, proposed by Macedonio et al. (2008) and Costa et al. (2009) for tephra fallout hazard assessment, could not guarantee the representativity at the scale of the simulation. Moreover, given that probabilistic hazard assessment require running thousands of simulations based on a set of input conditions, it is necessary to constrain the meteorological dataset, in order to reduce the number of simulations but ensure the representativity of the input conditions used.

The first example of hazard assessment for airborne ash concentration is presented by Papp et al. (Papp et al., 2005) who used a 7-years database of gridded meteorological data for initializing the TTDM. Folch and Sulpizio (2010) selected on a representative year, for which the meso-scalar model WRF (Michalakes et al., 2001) was run and coupled off-line with the FALL3D TTDM (Costa et al., 2006; Folch et al., 2009). The adoption of the representative year allowed a reduction of the time period for the meteorological simulations, and the representativity of the selected year was checked a posteriori against long-term daily means. Finally, the other example of tephra dispersal hazard assessment was published by Leadbetter and Hort (2011), based on U.K. MET Office meteorological data. The authors modeled a eruption every 3 hours for a 5-years period, running more than 17.000 numerical simulations. Nowadays there is still no common methodology for defining representative meteorological conditions on which to build probabilistic tephra dispersal hazard maps.

This overview points out that tephra hazard modeling strategies depend on many factors, and in particular on the availability of input data from field and observations. The timescale at which the outcomes will be used is also an important factor, and depends on the specific end-user requirements (in this case, aviation purposes). Finally, it is worth noticing that modeling strategies are also subjected to changes due to new regulations and new scientific and technological findings.

2.1.2 Open issues and specific objectives

The volcanic eruptions of Eyjafjallajökull (Iceland, 2010) and Cordón-Caulle (Chile, 2011) underlined the need to improve tephra dispersal modeling strategies used to forecast volcanic ash concentration at short term, in order to increase response capabilities and improve emergency management. In addition, and due to the increased risk perception towards such events, a higher attention has been posed on long-term hazard assessment, that allow increasing preparedness and reduce expected losses. After 2010, the scientific community together with involved stakeholders identified key issues to be addressed and solved in the near future. An overview of key issues and cutting-edge methodologies can be found in the conclusions of the Consensual Document from the 1st Ash Dispersal Forecast and Civil Aviation Workshop, held in Geneva in 2010 (Bonadonna et al., 2011a). The main critical aspects for the development of TTDMs and related tephra hazard modeling strategies are:

- Definition of representative meteorological conditions. Long-term hazard assessment builds on merging many simulations under different meteorological conditions statistically representative of the long-term conditions. Typically, hundreds to thousands of simulations must be considered with wind conditions sampled from a meteorological dataset (Bonadonna, 2006). This strategy, feasible for semi-analytical models, increases the computational cost of producing tephra dispersal hazard assessment. In particular, in case of local-scale simulations, due to the high computational cost of running NWPM and TTDM models, it is crucial to limit the number of simulations circumventing their computational cost. When this research activity started, there was not a common strategy for the production of probabilistic 3D tephra dispersal hazard maps at local scale, and only few examples of at regional scale (Papp et al., 2005; Folch and Sulpizio, 2010; Leadbetter and Hort, 2011).

- Definition of eruptive scenario. Definition of the eruptive scenario must be improved. In particular, the scenario should take into account the uncertainties associated to ESPs. Costa et al. (2013) proposed the use of Probability Density Functions (PDF) for the definition of ESPs. There are several example of application of PDF to produce a probabilistic hazard assessment of tephra accumulation at ground (Connor et al., 2001; Bonadonna et al., 2005). However, at the beginning of this research, there were no examples of probabilistic tephra dispersal hazard assessment based on fully-numerical modelling that used PDF for the definition of ESPs.

- Focus on aviation needs. Recent developments show that there is a growing attention on TTDMs strategies and a general need for adapting these strategies to the specific aims of aviation stakeholders. In particular, aviation stakeholders require to decrease the time interval at which the ash dispersal forecast is issued, and at the same time there is a strong criticism on uncertainties related to TTDM outputs. An increasing number of institutions and scientific groups are making a strong effort towards the improvement of the existing modeling strategies. However, this is still an ongoing process due to the recent changes in regulation and the differences in response strategies and procedures, defined by each specific stakeholder.

- Implementation of cutting-edge modeling techniques at operational level (in particular, data assimilation and ensemble forecasting). Data assimilation is the process of updating model input parameters with data coming from real or near real-time observations. Ensemble forecasting is the process of combining different modeling results, and can be performed combining several forecasts initialized with different ESPs, or combining results from independent simulations, obtained running different models (with the same ESPs). Galmarini et al. (2004) showed that ensemble techniques correctly performed can introduce a substantial improvement of modeling results.

- Communication. Outcomes of the 1st Ash Dispersal Forecast and Civil Aviation Workshop (Bonadonna et al., 2011a) underlined the need for improving communication between different actors involved in aviation management during explosive volcanic eruptions. In particular, communication of uncertainties was recognized to be a critical issue. The adoption of a probabilistic framework was suggested in order to account for the uncertainty associated to the TTDM outputs. Another critical aspect is the graphical output of the official VAACs forecasts, questioned during the 2012 IVATF meeting (IVATF, 2012). Recently, VAACs started to produce new types of volcanic ash forecasts to accomplish these community requirements (ICAO, 2012b; IAVWOPSG, 2014). Other institutions, like EUROCONTROL, are developing new tools to visualize ash dispersal forecasts in case of volcanic ash contaminated airspace (Bolić and Sivčev, 2012). TTDM graphical output is likely to be improved in the future.

The open issues identified by the community put the basis for the definition of specific objectives of this research, presented in Table 2.2. The aim of this research is to improve modeling strategies with the specific aim of supporting civil aviation management at for both long (hazard and vulnerability assessment) and short (aviation crises during an eruption) term.

Regarding long-term, two major issues during the computation of probabilistic hazard maps are the choice of the meteorological dataset and the definition of the ESPs. One objective of this research is to contribute to tephra hazard modeling strategies by defining representative meteorological dataset and producing probabilistic tephra dispersal hazard maps. In addition, this research intends to establish a methodology to perform probabilistic tephra dispersal hazard assessment accounting for the variability of ESPs. Current short-term TTDM strategies do not automatically provide civil aviation authorities with a volcanic ash forecast in a easy-to-use format (IVATF, 2012). A better post-processing and visualization of data, focused on aviation needs, would improve the information flow between scientific community and decision makers (Fox and Hendler, 2011). This research aims at enhancing the post-processing of TTDM outputs in order to be visualized by involved stakeholders. This would also support the subsequent impact assessment tool in a timely manner.

Table 2.2: Specific objectives regarding ash dispersal modeling strategies analysis

TIMESCALE	OPEN ISSUES	SPECIFIC OBJECTIVES
Long-term	Representative meteorological conditions	Methodology for identifying representative meteorological conditions
	Definition of expected scenarios and ESPs	Methodology for defining eruptive scenarios and ESPs
	No modeling strategies for aviation needs at reasonable computational cost	Methodology for producing hazard assessment for aviation
Short-term	Few specific forecast products for aviation stakeholders	Effective post-processing of modeling results, focused on aviation needs
	Cutting-edge modeling techniques	Account for recent development for aviation purposes

2.2 Vulnerability and impact assessment

This section reviews the state-of-the-art of vulnerability and impact assessment. Having defined the concept of vulnerability and other concepts related to it (resilience, impact), examples of vulnerability and impact assessment of volcanic ash dispersal on aviation are reviewed. This section also describes existing impact assessment tools for air traffic management during explosive eruptions. Given the novel character of this research, few works exist on this issue. Thus, the revision of the state-of-the-art includes studies on related topics, that provide useful insights and support this research. In addition, this section describes cutting-edge techniques currently being introduced and adopted by stakeholders involved in this field, pointing out the main open issues. Finally, based on this review, specific objectives are defined in order to improve current vulnerability and impact assessment methodologies and define new tools for managing air traffic during explosive volcanic eruptions.

2.2.1 State-of-the-art of vulnerability and impact assessment

Generally speaking and within the frame of natural hazards, vulnerability is the predisposition of the exposed elements to be affected, damaged or destroyed by a hazardous event. A theoretical overview and a collection of vulnerability definitions can be found in Cutter (1996), while an overview of assessments performed in different contexts can be found in the book of Menoni and Margottini (2011). The vulnerability of an element is defined in relation to a certain external solicitation, so that an element is vulnerable in different ways to different hazardous phenomena (Minciardi et al., 2006). Vulnerability should be therefore evaluated separately for each hazard (multi-hazard approach) and results synthesized in a global vulnerability assessment.

Although vulnerability is an intrinsic property of the exposed element, it is difficult to consider vulnerability without mentioning the impacts. In fact, empirical data collected in active volcanic areas are useful to characterize the vulnerability of the exposed assets. Moreover, localized damages can trigger cascading effects that influence the vulnerability at different temporal and spatial scales. Thus, the characterization of impacts on different elements often allows inferring the underlying vulnerability. Finally, vulnerability is related to the concept of resilience, defined as the capability of a physical element or an entire society to cope with hazardous phenomena and its consequences (Menoni and

Margottini, 2011) and to develop response strategies to reduce impacts.
The concept of vulnerability has two aspects: physical and systemic. Physical vulnerability is based on the physical interaction between the hazardous event and the single element, while systemic vulnerability takes into account the effect of a physical failure on a complex system and its interactions (Menoni and Margottini, 2011). Both physical and systemic vulnerability can be reduced by mitigation measures, and assessed using specific tools.

- **Physical vulnerability:** The aim of a physical vulnerability assessment is to define the specific vulnerability of each element of a system, for each hazard under consideration. Vulnerability assessment is usually based on indicators, defined according to the characteristics of the elements that increase/decrease their vulnerability. In some cases, physical vulnerability can be characterized by fragility functions, which allow quantifying the vulnerability of elements with increasing hazard levels. But fragility curves are not available for most natural hazards, with the exception of seismic hazard. A common methodology in absence of fragility curves is to assume a constant vulnerability value for exposed elements with given characteristics (Douglas, 2007). Traditionally, vulnerability studies for volcanic hazards have focused only on the physical dimension of vulnerability. First physical vulnerability studies were developed for pyroclastic density currents, due to their high impact on human lives (Spence et al., 2005b; Zuccaro et al., 2008). Physical vulnerability studies have also been performed for tephra fallout, due to its wide range of impacts on most human activities and assets, including buildings (Pomonis et al., 1999; Spence et al., 2005a; Zuccaro et al., 2013), infrastructural systems and productive activities (Stewart et al., 2006; Stewart et al., 2009; Wilson et al., 2009; Wilson et al., 2011; Wardman et al., 2012).
  The few existing examples of physical vulnerability studies for air traffic network are focused on two physical elements: airports and aircraft. Airports hundreds of km away from a volcano can potentially be disrupted by a weak tephra fallout, as few millimeters of ash deposited at ground impede normal airport operations (Casadevall, 1993; Guffanti et al., 2008). Cleaning operations are often difficult and time-consuming, especially under adverse meteorological conditions (Casadevall, 1993; ICAO, 2007). Finally, the remobilization of tephra at ground can

disrupt aviation operations, especially in dry and windy areas such as some regions of Argentina (Casadevall, 1993). However, the most hazardous phenomenon to civil aviation is tephra dispersal: airborne ash can disrupt flying operations at regional scale for days to weeks, as occurred during 2010 Eyjafjallajökull eruption in Europe. The main impact for an aircraft flying through high concentrations of volcanic ash is due to the ash melting in the engines, which can lead to engine stall (Casadevall, 1994). A description of past encounters and their consequences on engines can be found in Casadevall (1993) and Casadevall (1994). Bursik et al. (2009) underline that jet aircraft tend to fly at the jetstream level, increasing the probability of encountering ash particles due to the prevailing ash dispersal at such level. In addition, volcanic ash can also cause long-term damages to aircraft. The abrasive effect of volcanic ash particles can affect the turbine surface and/or cause significant damage to the exposed surface of the aircraft fuselage. These impacts do not affect the normal operation, but result in long-term damages, and life cycle of an affected engine can be considerably reduced. This phenomenon, although not producing serious consequences for human lives, can cause economical losses to private companies due to the high cost of maintenance operations.

During the 2010 Eyjafjallajökull eruption, a high attention was put on the definition of physical impacts of ash on aircraft. Until 2010 the air traffic operations were prohibited in presence of any detected volcanic ash, based on the so-called "zero tolerance" criterion (ICAO, 2007). However, during the 2010 crisis, the closure of a substantial part of European airspace caused many objections within airlines and general public. The European Commission gave the mandate of solving the crisis to EUROCONTROL, that proposed to allow flight operations in areas contaminated by the lower levels of ash concentration (Bolić and Sivčev (2011)). The UK Civil Aviation Authority (CAA) produced the first official quantitative ash charts, based on the values of 4 and 2 mg/m^3 were initially introduced to identify the areas of high and medium contamination, corresponding to no-fly zones and restricted fly-zones respectively (Civil Aviation Authority (CAA), 2010; IVATF, 2010a). However, the value of 2 mg/m^3 was finally established as quantitative threshold (IVATF, 2010b; ICAO, 2010) for the European airspace. Avoidance based on visible/discernible criterion has been proposed, but unfortunately there is still no agreement on the definition of "visible" and "discernible" ash (IVATF, 2012; EASA, 2012). Finally, since 2012 EASA adopted the Safety Risk Assessment (SRA) procedure, that allows operations in low-contamination airspace, if performed in compliance with the safety regulation (EASA, 2012).

The introduction of quantitative thresholds represents an important step forward in the definition of new strategies for crisis management, but there is still no universal agreement in their use. The introduction of quantitative thresholds poses the basis for quantitative impact assessment that allows identifying expected impacts on air traffic network components (airports, aircraft). However, the lack of well-defined tolerance values for aircraft engines limits the development of strategies to better manage the presence of volcanic ash in the aerial space (Bolić and Sivčev, 2011). The evolution of the ash concentration thresholds after 2010 eruption is synthesized in Table 2.3.

First ash concentration hazard maps were based on quantitative thresholds (e.g. 10-100 mg/m^3, Folch and Sulpizio, 2010 and 10^{-14}-10^{-15} mg/m^3, Leadbetter and Hort, 2011). According to Folch and Sulpizio (2010), ash concentration of 0.1 mg/m^3 can impact aviation operations. However, the adopted thresholds differ of many orders of magnitude. The first ash dispersal hazard assessment based on official quantitative threshold introduced by U.K. CAA was developed within this PhD (**Paper I**. Nowadays, experiments performed by manufacturers show that their engines can operate under ash concentration of 2 mg/m^3 (Haselbach, 2010; Emmott, 2010; Monso, 2010; Clarkson, 2013), but there are only a few scientific publications about this topic (e.g. Drexler et al., 2011), mainly because the information is still confidential and the manufacturers are developing private research.

- **Systemic vulnerability.** The importance of the systemic aspect of vulnerability

Table 2.3: Evolution of thresholds after 2010 eruption.

YEAR	THRESHOLD	DOCUMENT
Before April 2010	"Zero tolerance"	ICAO (1997)
April-May 2010	0.2 - 2 - 4 mg/m^3	CAA (2010), EASA (2010)
May 2010	0.2 - 2 mg/m^3	IVATF-1 - WP/21(2010)
July 2010	2 mg/m^3	IVATF-1 - DP/5 (2010)
June to November 2012	visible/discernible	IVATF-4 (2012); EASA (2012)

has been underlined in recent times by natural phenomena that, in some cases, led to catastrophic consequences (e.g. 2011 Japanese tsunami or 2012 Sandy hurricane). After these hazardous events, the attention on the indirect effects caused by physical damages has increased and today is a key aspect for risk managers and governments. However, in volcanology, there are only few examples of systemic vulnerability assessment, and none regarding tephra dispersal impacts.

Some pioneering studies on systemic vulnerability were developed for tephra fallout (e.g. Wilson et al., 2009; Wilson et al., 2011; Wardman et al., 2012). Wilson et al. (2011) introduced the concept of vulnerability of an infrastructural system, posing the basis for the application of the systemic approach in risk management. Also, the European project ENSURE (Contract 212045) is one of the few examples of vulnerability assessment from multiple hazard sources (ENSURE project, 2011). Results produced for the case study of Vulcano island (Italy) show how tephra deposition can affect the whole infrastructural system and produce indirect impacts on human activities, affecting the whole socio-economic system (Belvaux et al., 2011; Galderisi et al., 2011). In addition, studies in other branches of natural hazards (e.g. landslides, seismic hazard) provide relevant insights for this research. For example, Minciardi et al. (2006) underlined the importance of studying the road network structure as a starting point for assessing the systemic vulnerability of a road traffic network to landslides.

Regarding the air traffic operations, the study of the network structure can support the identification of relationships and hierarchies between the main elements of the whole system (Bel and Fageda, 2007; Wegner and Marsh, 2007) or specific segments of the market (commercial, freight, charter, low-cost aviation) (Burghouwt and Hakfoort, 2001; Francis et al., 2004). Redundancy is also identified as an indicator of how many alternative solutions are available in case of local failure (Kröger, 2008; Utne et al., 2011; Kjølle et al., 2012; Menoni et al., 2012). The only existing study where the vulnerability of the European air traffic network is related to natural hazards is that of Wilkinson et al. (2011) who discuss some properties of the air traffic network and describe the vulnerability to spatially-directed attacks. They demonstrated that the European air traffic system is a scale-free network, meaning that it has a high resilience to random attacks, but low resilience to driven attacks to hubs. Thus, understanding the interactions between the elements of the system is crucial for a long-term management (Hustache et al., 2011).

Besides the direct impacts of volcanic ash dispersal on air traffic sector, the Eyjafjallajökull eruption pointed out the wide dimension of indirect impacts on productive activities. Before 2010, there were very few studies on the quantification of economic impact of volcanic eruptions on the air traffic. The description of the economic disruptions produced by the eruption of Redoubt volcano was the very first (Tuck et al., 1992). The 2010 aviation disruption in Europe caused serious economical consequences, affecting not only the aviation sector (IATA Economics, 2010; IATA Economics, 2012) but also several stakeholders indirectly affected by its impacts (Sammonds et al., 2010; Jones and Bolivar, 2011). The interest in economic impacts of aviation crisis increased dramatically, together with the attention to the social dimension of vulnerability. Mazzocchi et al. (2010) proposed a methodology to account economical losses and the redistribution of benefits due to the air traffic disruption caused by the 2010 crisis. Socio-economic impacts of the Eyjafjallajökull eruption and the subsequent air traffic disruptions have been discussed in 2010 by the European Commission and the International Volcanic Ash Task Force (IVATF, 2010b). Resilience has been also identified as a relevant aspect to be taken into account (Cutter et al., 2003; Paton et al., 2001). However, there are no specific studies on the evaluation of social vulnerability and resilience of communities to the volcanic ash dispersal phenomena, mostly because it is a secondary hazard compared to other volcanic phenomena.

Both physical and systemic vulnerability may be decreased acting directly on the main exposed elements (i.e. aircrafts engines). On one hand, aircraft engine tolerance may be increased by the use of new materials (Drexler et al., 2011). In addition, the definition of tolerance for new engines would imply the renovation of aircraft fleet and the modifications of current standards. Thus, this option is not feasible at short and medium-term. On the other hand, systemic vulnerability can be reduced by identifying vulnerabilities of the exposed assets, and increasing preparedness of the system, focusing on its critical features. These options are more feasible but nowadays there are no examples of such practices.

- **Mitigation measures.** Some initiatives have been taken by the aviation stakeholders in order to improve risk management during eruptions, with the aim of increasing preparedness and decrease economic losses. Most of these were focused on European Air Traffic Management (ATM) services in case of eruptions, which ensure the required level of aviation operations at the available airspace capacity. ATM systems facilitate the planning of delays and the re-organization of flights during emergencies (e.g. strikes, adverse weather conditions) and the management of FIR (Flight Information Region) capacity and allow reducing the impact of air traffic disruptions, in order to maximize efficiency (Leal de Matos and Ormerod, 2000). However, before 2010, ATM procedures specifically designed for volcanic ash contamination were limited to ash avoidance (ICAO, 2007). It is also worth mentioning some initiatives taken at global level that may promote the integration of studies on volcanic eruptions and its impacts in a general natural hazard management framework.

– There is a standardized procedure in case of volcanic eruption. The Volcanic Observatories, in charge of the monitoring, notify the eruption onset to VAACs. VAACs issue the Volcanic Ash Advisory (VAA), while the Meteorological Watch Office (MWO) produce and dispatch the Significant Meteorological Information (SIGMET) and the Notice To Airmen (NOTAM). This procedure has been maintained after 2010, although having showed several debilities (Bolić and Sivčev, 2011).

– After the Eyjafjallajökull crisis, new ICAO "Volcanic Ash Contingency Plan" was issued for European and North Atlantic (EUR/NAT) regions, introducing new procedures in case of volcanic activity (ICAO, 2010). ICAO also instituted the International Volcanic Ash Task Force (IVATF). IN 2012 the ICAO task force meetings (IVATF, 2012) stated that the airlines have the possibility to decide how to act in presence of volcanic ash. This is conditioned to the approval of a Safety Risk Assessment (SRA) plan, presented by the airlines to the corresponding national authority. The existing volcanic eruption exercises, called VOLCEX and leaded by EUROCONTROL, were improved and used for testing new procedures (Sivčev, 2011) such as the new contingency plan (IVATF, 2011) and the possibility for airlines to decide whether to fly or not in the contaminated area. A description of the exercise can be found in Bolić and Sivčev (2012).

– In Europe, decisions are often taken at an international level, and recent procedures favor the centralization of information to contribute to a better management of forthcoming aviation impacts due to volcanic eruptions. In

2004, the Single European Sky (SES) was created to ensure the modernization of the European Air Traffic Management (ATM) system (SESAR, 2006). SESAR (Single European Sky Initiative) is the mechanism which coordinates and concentrates all European research and development activities in ATM. It aims at facilitating the information flow within the European air traffic system. In Europe, EUROCONTROL has been designated as the network manager, whose aim is to coordinate the response to air traffic disruptions in the SES and centralize flying operations. In case of volcanic eruption, EUROCONTROL maintains its role as a service provider, but has neither the task nor the responsibility of judging the airlines choices (Sivčev, personal comm., 2012), especially after the introduction of the SRA.

– The 2010 crisis caused many reactions also at worldwide level. The existing forecast and monitoring systems (e.g. Webley and Mastin, 2009; Webley et al., 2009) were enhanced by a standardization of the USGS Volcano Alert Level System (VALS) (Fearnley, 2011; Fearnley et al., 2012). This standardized alert system, together with the enhancement of monitoring systems at many Volcano Observatories, put the basis for more effective warning systems to support aviation operations worldwide (Guffanti and Miller, 2013). Finally, other international organizations such as IFALPA (International Federation of Air Line Pilots Association) underline the role of pilots in the decision-making process (Vujasinović, 2012) and suggest the adoption of a "pilot-in-charge" paradigm. All these regulations and initiatives put the basis for implementing response and design strategies to deal with ash-contaminated airspace.

The ongoing development of specific regulation and response strategies can support a faster and more efficient response during eruptions, eventually lowering impacts. There are only few documented examples of response actions performed during volcanic eruptions. Ulfarsson and Unger (2011) describe the strategy applied by Icelandair during the 2010 crisis. The company performed a rerouting of aircraft to a secondary hub in northern U.K., which led to a substantial reduction of losses. However, for these techniques to be adopted at wider scale, it is necessary to forecast expected impacts and plan response strategies and mitigation measures. At present, there are no such methodologies for vulnerability and impacts assessment on air traffic network in case of volcanic eruptions.

- **Existing tools.** Recent regulations and new protocols are expected to support an effective response during volcanic eruptions, but need to be implemented and automated effectively and in a timely manner. Normally, aviation stakeholders involved in ATM make use of specific software and tools, but at the beginning of this research, there was only one tool specifically developed for ATM during explosive volcanic eruptions, discussed below.

  The spatial dimension of hazard and vulnerability is recognized as a relevant aspect to be taken into account, and many authors suggest the use of Geographic Information System (GIS) for vulnerability analyses (Fekete et al., 2009; Lirer et al., 2010; Biass et al., 2012). GIS can be defined as "computer-based information systems that enable capture, modeling, storage, retrieval, sharing, manipulation, analysis and presentation of geographically referenced data" (Worboys and Duckham, 2004). GIS are thus particularly suitable for multi-layered visualization (Maguire et al., 2005) and spatial decision-making (Eldrandaly, 2007), and in particular for risk management (Radke et al.; Pareschi et al., 2000). GIS were developed in the 60s but their scientific use strongly increased during the 80s when computer became widely available. Nowadays, GIS have a wide range of applications (Goodchild, 1993).

  There are a few examples of application of GIS to the vulnerability assessment in case of volcanic hazards (Spence et al., 2005b; Spence et al., 2005a). VORIS (Felpeto et al., 2007) was the first GIS-based tool that allowed performing a multi-hazard assessment of volcanic hazards through the use of different models. First examples of integration of GIS-based hazard and vulnerability assessment were can be found in Biass et al. (2012) and Scaini et al. (2014).

  The attention posed by aviation stakeholders on spatially-based analysis and GIS tools has been increasing in the last decades. GIS have been traditionally used for local issues such as airport management (Hamzawi, 1986; Rong and Songchen, 2005; Du and Yuan, 2009). Wilkinson et al. (2011) suggest the use of GIS for vulnerability analyses of air traffic network in case of spatially-based hazards. However, GIS applications in ATM are very rare, mainly because atmospheric processes involve large amounts of data and 3D analyses. ATM operations, in fact, are in general based on Decision Support Systems (DSS), a specific type of

computer-based Information Systems (IS) that support decision-making activities, introduced in the latest 60s (Ferguson and Jones, 1969) and widely adopted since the 80s for ATM support (Keen, 1987; Deguang, 2001; Ma et al., 2004). Nowadays, ATM systems have reached a high level of complexity, and specially designed DSS systems have been developed for flight allocation, departures management, delay minimization and re-routing (Leal de Matos and Powell, 2003; Dell' Olmo and Lulli, 2003; Castelli and Pellegrini, 2011; Andreatta et al., 2011).
DSS systems for aviation are very specialized, and its use is limited to specific operators (e.g. controllers) and tasks (e.g. traffic direction). The main limitation of DSS is that, in general, are not suitable for advanced data visualization or management of different sources of spatial data (Lilburne et al., 1997; Eldrandaly, 2007). However, this capability is not required for safety-related tasks performed by controllers. Spatially-based DSS can also be applied to ATM for solving specific problems, for example planning of atmospheric research flights (Rautenhaus et al., 2012). Tools for ATM anr risk-management tasks during volcanic eruptions would have a different set of target users, some of them interested in analyzing different hazard and impact scenarios. Their requirements may be fulfilled by GIS tools, that allow supporting decision-makers in spatially-based problems (Eldrandaly, 2007). However, GIS tools also have limitations in exploring different choices (Malczewski, 1999). Table 2 presents a general comparison of GIS and DSS (Table 2.4). The coupling between DSS and GIS seems to be a good solution for the support of spatially-directed decisions (Chang et al., 1997; Sugumaran et al., 2004; Eldrandaly, 2007). In particular, GIS tools for aviation management during eruptions can be interfaced or complemented with other aviation-related DSS, The increasing use of spatial DBMS (Database Management Systems) together with the diffusion of web-based map services may in future enhance the integration of DSS and GIS into more powerful GIS-based DSS.

The only example of a GIS-based ATM tool for short-term analysis is the SAAM model (System for traffic Assignment and Analysis at a Macroscopic level, Eurocontrol, 2014c), developed by EUROCONTROL for private use. After the 2010 volcanic crisis, a map-based tool was developed specifically for volcanic-ash visualization: EVITA, the European Crisis Visualization Interactive Tool for ATFM (Air Traffic Flow Management), developed by EUROCONTROL (Eurocontrol, 2014a).

Table 2.4: Differences between GIS and DSS

GIS	DSS
Quantitative and suitable for structured problems	Qualitative and suitable for non-structured problems
Use geometric features	Use symbols
Integrate data	Integrate knowledge
Do not easily handle incomplete data	Handle incomplete data and knowledge
Spatial analysis capability	No spatial analysis capability
No inference/reasoning capabilities	Inference/reasoning capabilities
Variety of output maps/graphics	Very specific mapping capabilities

EVITA is a GIS-based tool specifically designed to support aviation management in case of ash-contaminated in airspace. At the moment EVITA is mainly a visualization tool (Fig. 2.1) with reduced analysis functions, rather than a complete tool to support decision-makers. For this reason, the portal is activated during aviation crises and allows airlines to gather some relevant information but the tactical choices are to be made independently by airlines (Sivčev, personal comm., 2012). This tool has been tested and used during the VOLCEX exercise obtaining

Figure 2.1: Screenshot of EVITA tool, showing the ash cloud from a NOP map. Figure from Bolić and Sivčev (2011).

positive results (Bolić and Sivčev, 2012). However, user feedback underlined the low user-friendliness of the EVITA Graphical User Interface (GUI). Another important instrument, with a more general purpose, is the NOP (Network Operation Portal), the EUROCONTROL central repository for all relevant information (Eurocontrol, 2014b). This web-based portal is currently used by most civil aviation stakeholders to manage their operations. The NOP portal played a central role during the Eyjafjallajökull volcanic crisis, when it received more than 13 million hits per day (EUROCONTROL) pointing out the need for stakeholders to refer to a common, reliable repository at European level.
These few existing map-based tools could enhance ATM capabilities during eruptions, as confirmed by the massive use of NOP portal and the overall positive feedback on the EVITA tool. However, at the moment each airline has a different approach for flight dispatch and related tasks (the flight planning in presence of ash being one of them). The tools and services adopted by airlines, including weather forecast services, depend on the specific business model and cost-benefit analysis implemented. Therefore, different airlines use different software packages to create and visualize their own flights. At the moment, the only free tool for ATM is EVITA, in Europe. There is also a WSI (WSI - professional division of the Weather Company, 2014) aviation forecast service that allows visualizing in Google Earth format the information from VAACs and/or other providers of ash dispersal forecast.

Since 2010, the attention to impacts caused by explosive eruptions on aviation has been increasing together with the interests of aviation community in impact assessment tools and mitigation strategies for loss reduction. However, there are very few vulnerability and impact assessment methodologies developed for this specific topic, and the application of new regulations requires the introduction of specific tools. This overview shows that vulnerability and impact assessment of air traffic system due to volcanic eruptions is a wide field that comprises many aspects (physical, systemic, socio-economic) and aims at supporting many different stakeholders. Although the initial concern was posed on the physical dimension of vulnerability, new regulations were defined in 2010 based on systemic and economic considerations (Ulfarsson and Unger, 2011). In fact, besides physical impacts, it is important to consider the systemic dimension of impacts of natural hazards on anthropic and infrastructural system, that can affect all branches of society (Birkmann, 2006; Birkmann, 2013).

Finally, it is worth noting that, when a volcanic crisis occurs, specific ATM tools are interfaced with the volcanic ash forecast coming from the VAACS at 6-hours interval. However, many stakeholders aim at using different sources of information for their analyses (outcomes from other TTDMs, satellite retrievals, private products), as underlined by an end-user survey performed by the VAST (Volcanic Ash Strategic Initiative Team) project (Prata and Zehner, 2013). The relationship between ash dispersal modelers and aviation stakeholders is thus very relevant for a correct aviation management during eruptions. Prior to 2010, there were no examples of surveys performed amongst the community involved in aviation management during eruptions, and when this research began (November 2010) the attention to end-users was still limited. The surveys performed on EVITA (Bolić and Sivčev, 2012) and by the VAST community (Prata and Zehner, 2013), together with the outcomes of other specific meetings (Bonadonna et al., 2011a; Bonadonna et al., 2013) pointed out the need for enhancing communication between aviation managers and scientific community. At the moment, there are still no examples of end-user surveys that can support the development of specific impact assessment tools aimed at supporting aviation stakeholders during volcanic eruptions.

2.2.2 Open issues and specific objectives

The summary of the state-of-the-art of aviation vulnerability assessment to volcanic ash dispersal underlines some open issues. This PhD research intends to answer to some of these issues with specific objectives defined in Table 2.5. The distinction between short and long-term timescale (section 1.2) is maintained here, although most of the concepts are applicable at both timescales.

One of the objectievs of this research is to propose a methodology for assessing vulnerability of the air traffic system to volcanic ash. The aim is to define indicators and techniques to estimate the two main types of vulnerability: physical and systemic. Moreover, this research attempts at estimating socio-economic vulnerability, currently not taken into account when managing aviation during volcanic eruptions. The proposed vulnerability and impact assessment methodology will be applied to the case study of the European air traffic network, where most of the new strategies are being applied.

Table 2.5: Specific objectives regarding vulnerability and impact assessment

TIMESCALE	OPEN ISSUES	SPECIFIC OBJECTIVES
Long-term	Vulnerability assessment of air traffic Systemic and socio-economic impacts	Vulnerability assessment methodology of air traffic Methodology that accounts systemic and socio-economic impacts
Short-term	Impact assessment for air traffic Few tools for ATM during eruptions	Impact assessment methodology for air traffic Development of a tool for ATM purposes
Both	New regulation under definition Critical thresholds for aviation not defined	Account for possible regulation developments Include different thresholds

Regarding short-term, there is a strong need for defining impact assessment methodologies in order to estimate expected impacts, and for specific tools to automate the impact analysis and support ATM stakeholders. This research will design a GIS-based tool to support civil aviation management during volcanic eruptions.

In addition, at both short and long-term, it is important to account for new regulation and open issues. In particular, a strong limitation in the development of this research is that the definition of ash concentration thresholds is still under debate. For this reason this research accounts for many quantitative thresholds that have been proposed after 2010.

A secondary aim of this research is to enhance the existing strategies for managing information flow between scientific and air traffic management communities during emergencies.

Chapter 3

Methodology

3.1 Modeling strategies for tephra dispersal hazard assessment

This section presents contributions of this PhD to the existing strategies for tephra dispersal hazard assessment, describing the methodologies at both long and short-term. The novel approaches introduced in this section have been applied to four case studies: Concepción volcano (Nicaragua), Vesuvius (Italy), Popocatepetl (Mexico) and 4 active volcanoes in Iceland. Results are respectively described in **paper I**, Sulpizio et al. (2012), **Paper II** and **Paper III**. Main results are summarized in this manuscript (chapter 4). Since 2010, the importance of long-term tephra dispersal hazard assessment for improving preparedness has been underlined by a growing fraction of the community (Bonadonna et al., 2011a). However, there is a clear need for producing long-term hazard assessment at active volcanic areas, in order to produce results tailored to aviation purposes.

This PhD proposes the application of methodologies that allow a better definition of TTDM inputs for the probabilistic tephra hazard assessment, which consists in running several TTDM simulations initialized with different combinations of input parameters. Long-term strategies, aimed at producing tephra dispersal hazard assessment, rely on meteorological data and eruptive scenarios (Fig. 3.1, left). Tephra dispersal hazard maps are produced by merging TTDM outputs produced by varying both volcanological and meteorological inputs (Fig. 3.1, right).

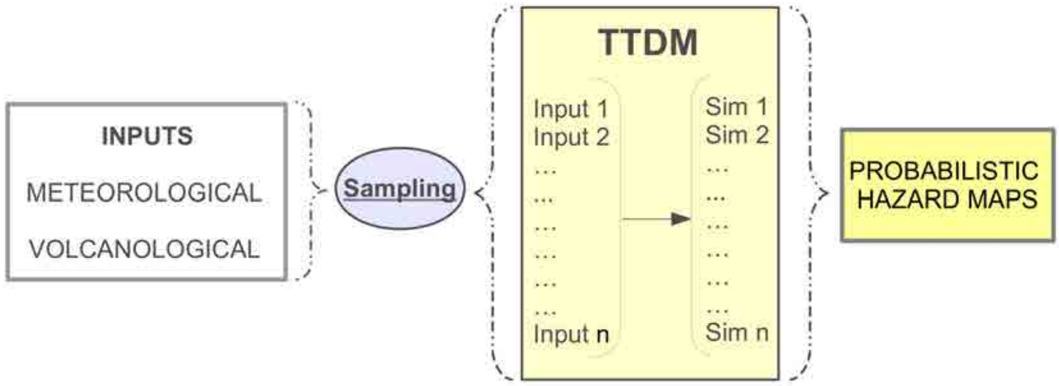

FIGURE 3.1: Long-term modeling strategy for probabilistic tephra dispersal hazard assessment. Inputs (left) are sampled in order to initialize several runs of the TTDM model (sim1...n), subsequently merged into probabilistic hazard maps (right).

In order to produce hazard maps, it is also necessary to select threshold values of the parameter for which probabilistic maps are built (in this case, ash concentration). Given that there is no consensus on the value to be adopted (Section 2.2.1 and Table 2.3), the quantitative thresholds introduced by CAA and used for quantitative ash dispersal forecasts in 2010: 0.2 and 2 mg/m^3 are adopted. It is worth noticing that before 2010, the range of thresholds adopted in ash dispersal hazard assessment was very wide: Papp et al. (2005) refer to a high concentration value but without quantifying it, while Folch and Sulpizio (2010) adopted values of 0.1 and 0.01 mg/m^3 and Leadbetter and Hort (2011) used lower values (10^{-12} to 10^{-15} mg/m^3). However, the avoidance criterion is still applied in many areas of the word. For this reason, probabilistic hazard assessment is also performed for a threshold of 10^{-6} mg/m^3, assumed for the zero-tolerance criterion. This PhD research contributes to the production of probabilistic tephra dispersal hazard assessment by proposing strategies focused on the characterization of meteorological representative conditions, eruptive scenarios and ESPs.

3.1.1 The Typical Meteorological Year (TMY)

One of the required inputs for performing a probabilistic tephra dispersal hazard assessment is the definition of representative meteorological conditions for the area at stake. The selection of long-term representative conditions at regional and global scale usually relies on a random sampling of meteorological conditions in a given time interval. For example, Papp et al. (2005) perform the simulations over 7-years meteorological data, and Leadbetter and Hort (2011) extract 17.000 samples within a 5-years meteorological

database. The existing examples of hazard assessment for tephra fallout (e.g. Macedonio et al., 2008, Costa et al., 2009) and the two example of tephra hazard assessment prior to the beginning of this research (Folch and Sulpizio, 2010; Leadbetter and Hort, 2011) apply different methods to select the long-term representative meteorological conditions. In particular, Folch and Sulpizio (2010) use a meteorological mesoscale model, WRF-ARW (Michalakes et al., 2001), for a year known a priori to be representative.
The choice of meteorological conditions is particularly critical at local scale, due to the high computational cost of running NWPM models prior to TTDM, that increase the computational cost of the hazard assessment. An output file produced by the WRF-ARW model for 72 hours occupies indicatively 5 Gb of disk space. Thus, running meteorological simulations at local scale for a long-term period (e.g. 10 years) can take produce more than 3 Tb of data and require considerable computational resources.
This research proposes a new method for defining representative meteorological conditions at local scale making use of the Typical Meteorological Year (TMY). The advantage of the TMY is that it reduces the number of meteorological simulations necessary to compute a hazard map at high resolution (i.e. at spatial resolutions for which mesoscale meteorological modeling is required). A TMY consists of 12 representative months selected from individual years of a time period (typically several decades) and collated in a meteorological database. This concept, introduced by Finkelstein and Schafer (1971), has been used in other fields such as climatology (Kalogirou, 2003) and solar energy characterization (Bulut, 2004; Bulut, 2010).
The original definition of TMY is for one meteorological variable and at a given point. The TMY has subsequently been adapted to the definition of a climatic TMY based on several variables, merged using a set of weights (Lam et al., 1996). However, it has never been used for the definition of a typical conditions for vectorial variable such as wind. The TMY is defined based on the Filkenstein-Schafer (FS) method, a statistical method selecting the 12 months with minimum difference from the long-term conditions (long-term makes reference to the whole temporal series of meteorological data used, for example 10 years). This research proposes an adaptation of the FS method to account for both wind speed and direction.

The FS method consists on:

1- Calculating the Cumulative Distribution Function (CDF) for each meteorological parameter. The procedure consists on grouping the values under a number of bins, and counting the frequency within each bin. The long-term CDF (CDF_l) is obtained considering the whole temporal series of the parameter (in our example, 10 years). The specific CDF for each month and year (CDF_s) is calculated separately for each month of data (for instance, the CDF_s of the wind speed of January of a given year). The first step is the minimization of the FS factor, defined as the mean difference of the CDF_l and the CDF_s over the total number of bins N_b. The FS factor is calculated for each month as:

$$FS = \sum_{i=1}^{N_b} |CDF_l - CDF_s|/N_b \tag{3.1}$$

To take into account the relative importance of the different meteorological parameters, a Weighted Factor (WF) is defined. The WF factor is calculated as the weighted sum of the FS factor calculated for wind speed (FS_1) and direction (FS_2), having weights w_1 and w_2 respectively:

$$WF = FS_1 w_1 + FS_2 w_2 \tag{3.2}$$

This allows ordering the months in the time period based on the WF value. The 5 months with lower WF are selected as candidates for the TMY.

2- The second step allows choosing which of the 5 selected months will be part of the TMY. To this aim, the Root Mean Square Difference (RMSD) is computed for each month having N_d days for each meteorological parameter (for example, for wind horizontal component v_i having average v_{im}):

$$RMSD = \sqrt{\sum_{i=1}^{N_d} (v_i - v_{im})^2/N_d} \tag{3.3}$$

Weighted Mean Square Difference (WMSD) is defined as the weighted sum between RMSD1 (relative to wind speed) and RMSD2 (relative to wind direction) having respectively weight w_1 and $w2$.

$$WMSD = RMSD_1 w_1 + RMSD_2 w_2 \tag{3.4}$$

The month having the lowest value of WMSD is considered the most representative of the long-term conditions.

The TMY method has been applied to the case-study of Concepción volcano (Nicaragua) as described in **Paper I**. In particular, TMY has been defined for vertical levels above the

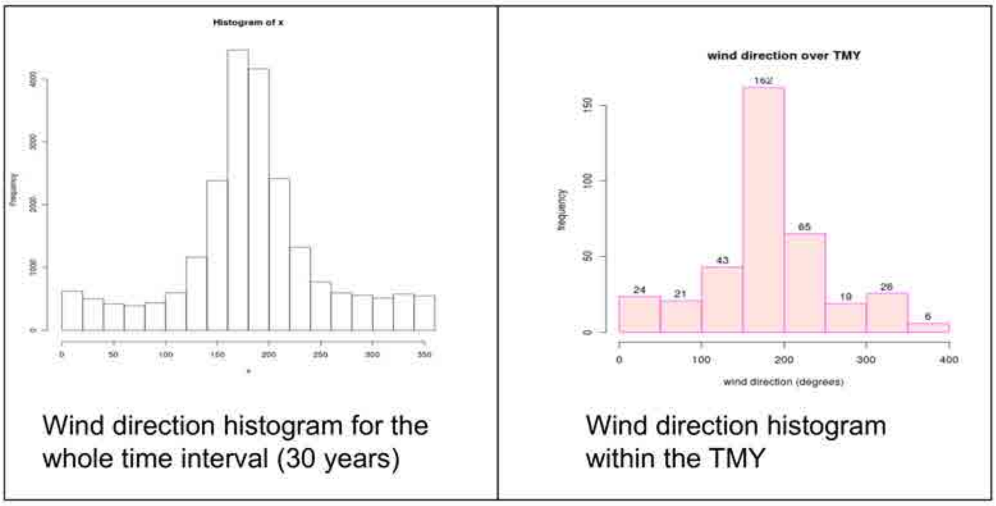

FIGURE 3.2: Comparison between the long-term CDF of hourly wind direction (left) and the TMY (right) at a given height above the Concepción volcano vent (i.e. 10 km s.l.m.).

volcano, corresponding to the average column height for the eruptive scenarios defined at the considered volcano (**Paper I**). Thus, a TMY has been associated to each scenario. Figure 3.2 shows the comparison between the CDF of hourly wind direction for the long-term temporal interval considered (left) and within the TMY (right) at a given height (10 km s.l.m.), showing a similar shape. Then, numerical simulations have been performed over the TMY, running the WRF model at 00.00 and 12.00 UTC. Each WRF simulation lasts 10 days and occupies approximately 12 Gb of disk space. The entire TMY thus occupies less than 500 Gb. The use of the TMY constrains the mesoscale meteorological simulations to one year (statistically representative of a much longer period) and makes the computation of hazard maps less computationally expensive. The TMY is therefore a good solution to decrease computational cost and storage constraints in case of local scale tephra dispersal hazard assessment. However, this method has some limitations, discussed in **Paper I**, and shall be improved in future, for example accounting for local variability of wind conditions in the surroundings of the volcano vent. To this aim, a TMY may be defined, for example, using not one but many points around the volcano. Finally, it is worth noticing that the adoption of this technique is increasing, due to its applications to renewable energy design and management (Al-Salihi, 2014; Ohunakin et al., 2014). Applications to wind speed have been proposed (Maklad, 2014) for wind energy generation, but do not account for wind direction.

3.1.2 Stratified sampling of ESPs using probability density functions (PDFs)

Probabilistic hazard assessment is build upon several runs of TTDMs, initialized with a set of ESPs corresponding to a given eruptive scenarios or multiple scenarios. Several runs of TTDM are then initialized with a set of ESPs and merged in order to build probabilistic hazard maps (Fig. 3.1).

The concept of probabilistic hazard assessment, initially developed for tephra fallout hazard assessment (Barberi et al., 1990; Bonadonna et al., 2005), is based on the definition of eruptive scenarios characterized by ranges of Eruptive Source Parameters (ESPs). Bonadonna et al. (2005) proposed the use of Probability Density Functions (PDF) in order to account for uncertainties associated to the ESPs. It is worth noticing that the definition of the PDF depends on the eruptive record, and that there are different approaches depending on the richness of field data and tephra stratigraphical studies. ESPs are selected by a random sampling within their probabilistic distribution, in order to produce probabilistic tephra fallout hazard assessment. However, exploring all the possible combinations of ESPs requires running thousands of simulations (Bonadonna et al., 2005), increasing the computational cost of the hazard assessment (Folch and Sulpizio, 2010). For this reason, the adoption of a statistical technique (i.e. the stratified sampling) is proposed, in order to reduce the representative population used for tephra dispersal assessment.

This sampling method is very common in social sciences because it allows identifying a representative subset of a population, assuming prior knowledge on its distribution (Särndal et al., 2003). Using the stratified sampling, this research produced probabilistic tephra dispersal hazard assessment based on PDF for ESPs. This technique has been applied to the probabilistic tephra dispersal hazard assessment at Concepción volcano, Nicaragua (**Paper I**) and Popocatépetl volcano, Mexico (**Paper II**.

The stratified sampling (Rao and Krishnaiah, 1994) is a statistical sampling method that allows the number of samples representatives of a given population to be reduced. This method assumes a previous knowledge about the probability distribution of a random variable. Having discretized each PDF into bins with an associated probability, the stratified sampling allows extracting ESPs according to the relative probability of each bin.

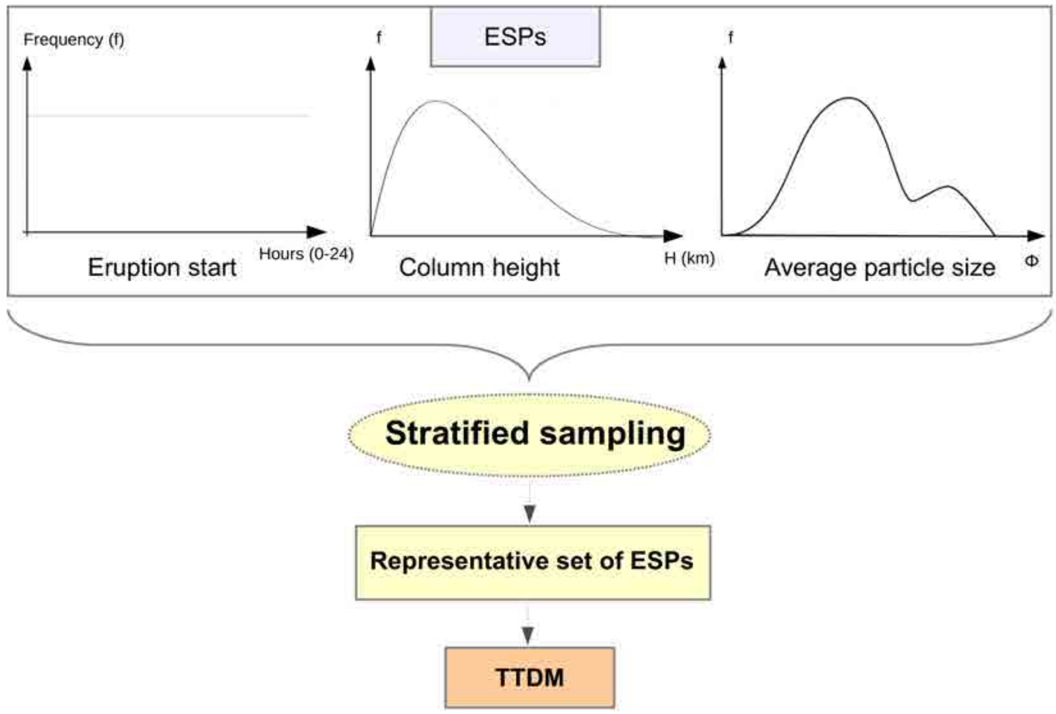

FIGURE 3.3: The stratified sampling technique allows extracting a representative subset of the input parameters (top) to reduce the number of TTDM runs (bottom) and maintain the representativeness of ESPs.

The main application of the stratified sampling is the definition of a statistically representative subset of ESPs from a given probabilistic eruptive scenarios. Inputs for the TTDM are in fact selected amongst the range of input parameters. Figure 3.3 shows an example for three input parameters (eruption starting date, column height and average particle size). However, this technique can be ideally applied to a wider set of parameters. In addition, the stratified sampling may be used to define the representative meteorological conditions at regional/global scale sampling within a time interval (similarly to Leadbetter and Hort, 2011). The fact of sampling over a long time-period ideally guarantees a statistical representation of the long-term meteorological conditions, but only with a high number of samples. The application of this sampling technique allows sampling the date of the eruption amongst a long-term time interval, for example hypothesizing a constant probability distribution over time. This results in a representative subset containing an equal number of samples for each month of the time interval, as performed in **Paper II** for selecting the meteorological conditions within a long-term period. The stratified sampling may also be used for studying specific months of interest, for example for seasonal patterns or extreme climatic conditions. Seasonal maps have been produced in **Paper I** and **II** dividing the simulations in different subsets. However, seasonal maps in future may be based on the prior selection of input parameters through ad-hoc stratified sampling.

3.1.3 Tephra dispersal hazard maps tailored to aviation

As underlined in section 2.1, one objective of this research is to enhance ash concentration charts in order to support aviation stakeholders. A complementary aim of the research is to improve the communication of outcomes of hazard assessment and its associated uncertainties.

This research contributed to the production of new types of maps of averaged persistence and arrival time, that allow visualizing the temporal distribution of expected hazards. Maps of averaged persistence and arrival time have been introduced in the coauthored work of Sulpizio et al. (2012) and Biass et al. (2014), respectively. Such maps are complemented with the calculated standard deviation of these parameters, in order to account for uncertainties (Biass et al., 2014, Appendix B). All maps are produced by merging several modeling outputs and calculating final values over the computational grid (Fig. 3.1).

The different types of maps produced during this research are:

- Probabilistic hazard maps of ash concentration. The probability of overpassing a given critical ash concentration threshold in each cell is defined as:

$$P[C(x,y,z,t)] \geq C_T|eruption] \tag{3.5}$$

  where C(x,y,z,t) is the tephra mass concentration in the atmosphere at a given point and time and C_T is the chosen mass concentration threshold. For a given eruption scenario, the probability of disruption P_c at a point P(x,y,z) is quantified by counting the number of times the considered threshold is exceeded over the total number of runs performed in the hazard assessment (N):

$$P_c(x,y,z) = \frac{\sum_{i=1}^{N} n_i}{N} \tag{3.6}$$

where

$$n_i(x,y,z) = \begin{pmatrix} 1 \text{ if } \mathrm{C}_i(x,y,z) \geq C_T|eruption \\ 0 \text{ otherwise} \end{pmatrix} \tag{3.7}$$

being $C_i(x,y,z)$ the concentration at a given point P(x,y,z) and at time step i.

It is worth noticing that for a given run, the occurrence of critical conditions (e.g. overpassing critical concentration) is accounted as a positive event for the probabilistic hazard assessment regardless of the number of model time steps during which the condition is verified.

- Maps of averaged persistence time. Persistence time is calculated by counting, for each run, the number of model time steps in which the critical concentration threshold is exceeded at a point P(x,y,z) of the computational domain. The average persistence time is then calculated over the values estimated for each run. Note that persistence time is accounted only if the overpassing of the ash concentration occurs for a minimum number of times (e.g. 5% of the total number of simulations performed).

- Maps of averaged arrival time. The first arrival time (hereafter referred to as arrival time) computes the time from the beginning of the eruption to the first detection of the critical concentration at a point P(x,y,z) of the computational domain. The average arrival time is then calculated over the values estimated for each run.

- Standard deviation maps for average arrival/persistence time. Both persistence and arrival time are quantified as mean (i.e. average value at a pixel over the entire number of runs) and standard deviation. The standard deviation is calculated over the average values estimated for each run, and allows estimating the uncertainty associated to the averaged persistence/arrival times.

All these types of maps can be produced at each FL of interest. However, maps comprehensive of all results at different FL are also useful to aviation stakeholders (Biass et al., 2014). Figure 3.4 shows an example of the different types of maps for the case of Katla volcano (Iceland). Results are comprehensive of all FLs. Such maps have been produced for 4 active Icelandic volcanoes (Biass et al., 2014, Appendix B).

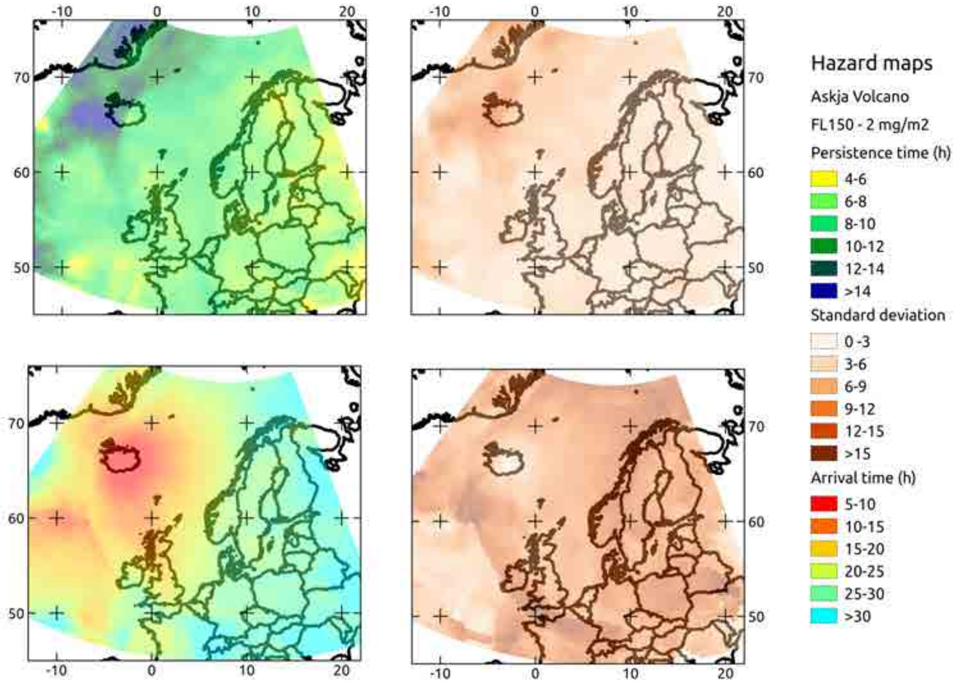

FIGURE 3.4: Maps introduced during this research: average persistence time and standard deviation (top, left and right respectively) and average arrival time and standard deviation (bottom, left and right respectively).

3.2 Vulnerability and impact assessment

This section describes the methodologies proposed for assessing vulnerability of the air traffic network to volcanic ash dispersal and to estimate its expected impacts. Following the distinction between short and long-term risk management, the vulnerability and impact assessment is performed at two temporal scales: long-term for territorial planning and short-term for crisis management. For the long-term case, a methodology has been developed to estimate and visualize the expected impacts of explosive eruptive scenarios on European air traffic network (**Paper III**). For the short-term case, this research produced a tool to quantify the expected impacts of volcanic ash on aviation. The tool has been applied to eruptive scenarios at two active Icelandic volcanoes: Eyjafjallajökull (Scaini et al., 2011) and Katla (**Paper IV**). The definition of scenarios used for both applications is described in the coauthored paper of Biass et al. (2014), attached in Appendix B.

3.2.1 Instruments and methods

This section presents the main instruments and method that form the basis for the development of the vulnerability and impact assessment methodology. The methodology is based on two tasks: spatial data management and spatial analysis. These operations are performed using two main instruments: spatial Database Management Systems (DBMS) and Geographical Information Systems (GIS). The use of these two instruments has been recommended by the scientific community and the aviation stakeholders (section 2.2). In this research, they are used for a specific aim: building a tool to support ATM during explosive volcanic eruptions.

DBMS systems allow storing, modifying and extracting information from a database through the universal SQL (Structured Query Language) language (Date, 1990). DBMS are widely used in several fields (Ramakrishnan and Gehrke, 2003) and in particular for supporting decision making (Marakas, 2003). GIS and DBMS are deeply interfaced, as GIS uses DMBS to store spatial entities and perform operations. The connection between GIS and databases is extremely important in terms of performance and efficiency of spatial operations. Most GIS rely on underlying DBMS, but only few allow direct interaction with DBMS functionalities. For example ArcGIS (Environmental Systems Research Institute (ESRI), 2011) is based on Microsoft Access or Oracle DBMS, while most open-source GIS are fully interfaced with open DBMS software (Neteler et al., 2012). Amongst open source GIS currently available (http://opensourcegis.org/), one of the most powerful is GRASS, initially developed by the US Army and then maintained and developed by the open source community (Westervelt, 2004). The specific GIS functionalities used in this research are:

- Pre-processing. GIS can be used to import and pre-process input data such as probabilistic ash concentration maps or ash dispersal forecasts. Usually, results of numerical simulations are binary files (grib, NetCDF and HDF5), which allow storing large amount of data in the form of time dependent variables (e.g. ash concentration) defined over a 3D grid, for each time step (Fig. 3.6). Although these formats are very compact and extremely useful for meteorological and numerical modeling communities, their low friendliness reduces their usability for most end-users, including aviation stakeholders. There are many tools that allow extracting information from NetCDF files, and amongst them libraries (for example nco,

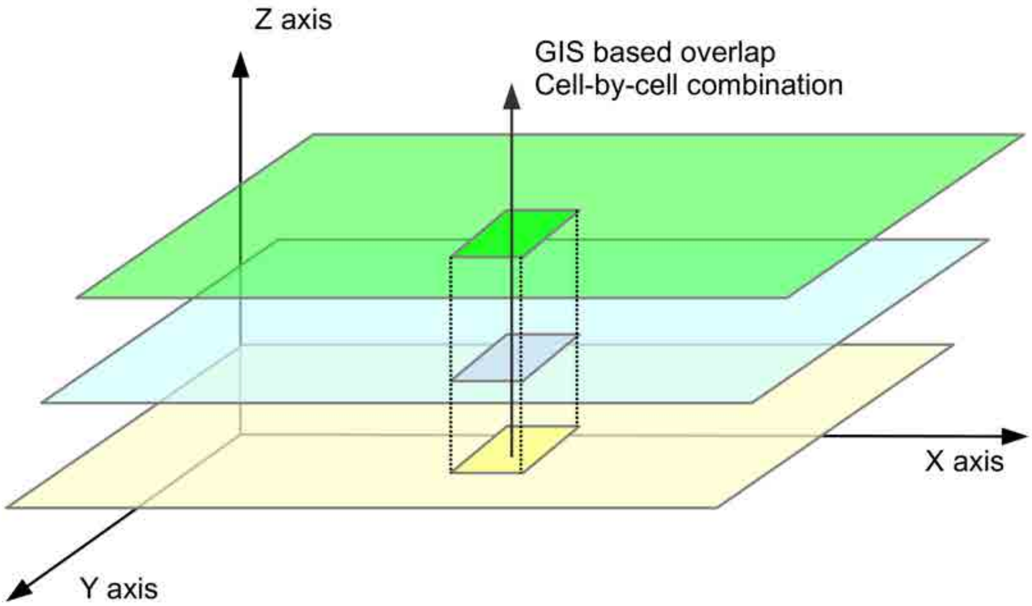

FIGURE 3.5: The overlap is a typical spatial analysis operation performed by GIS and allows combining different sources of information on a cell-by-cell basis.

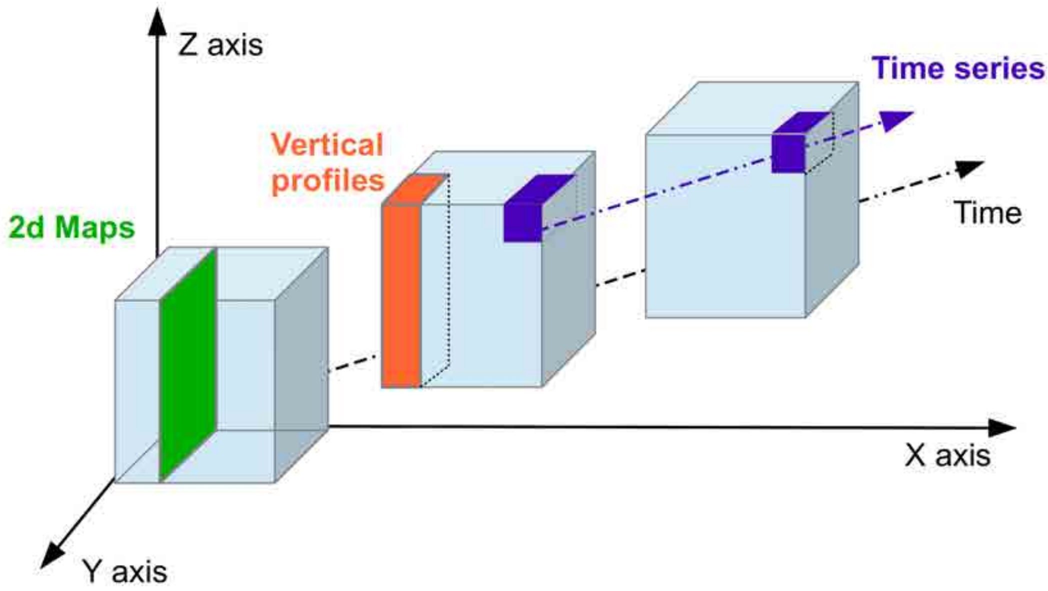

FIGURE 3.6: Typical structure of a NetCDF, that allows storing many variables (some of them time dependent) in a 3D grid, for each time step.

http://nco.sourceforge.net/) and programs such as GRASS (Neteler et al., 2012). In particular, GRASS allows the automated extraction of relevant information and enables the production of hourly ash dispersal charts. GIS can also be used to import and pre-process air traffic data. Air traffic features contained in the air traffic database can be converted into spatial entities that support spatial operations such as intersection or union. Airports are stored as points, flights are stored as lines constituted by segments that connect waypoints (Scaini et al., 2011, Appendix B), and airspace sectors are stored as polygons.

- Data management. GIS systems rely on specially designed DBMS that allow storing and managing spatial elements, stored into two main data types: vector and raster data (Rigaux et al., 2001). Both data types allow the representation of real elements. Vectorial features are represented through points, lines and polygons, while raster features are constituted by pixels. All spatial elements are associated to coordinates (stored as attributes of the elements) and metadata (e.g projection).

- Spatial analysis. One of the most important tasks performed by GIS programs is spatial analysis, that is, cell-by-cell operations over digital maps. A typical spatial analysis operation is an overlap (Fig. 3.5). The overlap is widely used in the impact assessment methodology, for example, for assessing expected impacts by overlapping hazard and vulnerability characteristics. Spatial analysis is also used for combining several maps into a final maps, performing operations on a cell-by-cell basis. For example, it allows producing maps containing the average value of a specific set of maps. Another typical GIS operation used in this research is the buffering, that is, the creation of a zone (normally radial) around a map feature measured in units of distance or time.

- Automation. A main advantage of using GRASS GIS is that it is scriptable, and allows automating procedures withing shell scripts. GRASS has a very efficient interface with the most powerful SQL DBMS (Neteler et al., 2012), while a limitation is the low user-friendliness compared to other GIS programs.

- Visualization. Many GIS enhance visualization of scientific datasets and spatial operations through a user-friendly GUI that allows performing spatial analysis from a friendly graphical environment, producing different outputs. For example, Quantum GIS (or Qgis) is a very diffused Open Source GIS due to its friendly and popular GUI. Nowadays, GRASS and QGIS are integrated (Neteler et al., 2012), making possible for an end-user to perform GRASS analysis through QGIS friendly environment. In this research, vulnerability and impact assessment results are produced in form of maps and tables. Maps are visualized through QGIS software.

During the initial phase of this research, a comparison of the existing open source DBMS (e.g. SQLlite, PostgreSQL and MyQSL) was performed. The selected DBMS has been SQLite (http://www.sqlite.org/) and its spatial extension Spatialite (http://www.gaia-gis.it/gaia-sins/). SQLite is a server-free database, and its structure allows to store all data into one file, making it easily portable and suitable for desktop applications. However, the methodologies presented in this research could be easily implement using other SQL-based DBMS. Spatialite is used for storing air traffic data: airports, routes and airspace sectors are stored respectively as points, lines and polygons. The spatial DBMS contains also hazard information (in raster format) imported from the TTDM output and results of vulnerability and impact assessment. The spatial database is interfaced with GRASS GIS, that allows performing spatial analysis operations. QGIS, that acts as GUI, allows visualization of results and further post-processing of results. In conclusion, the combined use of GRASS, QGIS and SQLite/Spatialite is the most suitable choice for the development of this research.

3.2.2 Long-term vulnerability and impact assessment of air traffic network

This section presents a methodology for long-term vulnerability and impact assessment of air traffic networks in case of explosive volcanic eruptions. The proposed methodology relies on the availability of hazard assessment results (Fig. 3.7, right). The long-term analysis is constituted by three main steps (Fig. 3.7): exposure analysis, vulnerability assessment and estimation of expected impact. Results of the application of this methodology to the European air traffic network are presented in Chapter 4. Chapter 5 presents a final discussion of the results and propose further developments.

1. **Exposure analysis.** Exposure analysis consists in identifying the elements of the system that can be affected by the hazardous phenomenon.
   On one hand, airports play an important role in the air traffic network providing a service to the surrounding areas. These features are exposed to both ash fallout

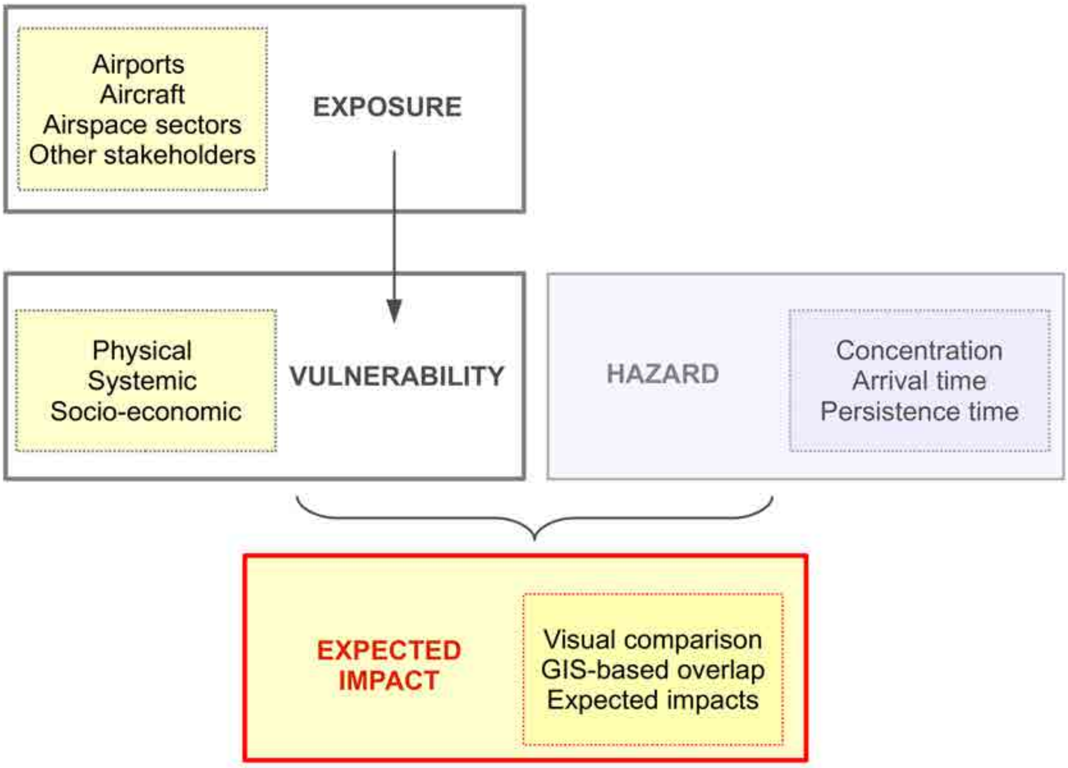

FIGURE 3.7: Long-term vulnerability and impact assessment methodology, constituted by exposure and subsequent vulnerability analysis (left) and hazard assessment (right), whose outcomes are combined to estimate expected impacts (bottom).

and dispersal. On the other hand, aircraft can be disrupted by ash in the atmosphere, disrupting relevant traffic connections and indirectly impacting local and regional economies. Based on these considerations, the exposed targets for the systemic vulnerability analysis are airports and routes in the area under study.

Aerial sectors represent a key component of the air traffic network because each sector has an associated capacity, which is the main parameter for air traffic management (Leal de Matos and Ormerod, 2000; Leal de Matos and Powell, 2003; Dell' Olmo and Lulli, 2003). Thus, in order to have a vulnerability assessment meaningful to civil aviation stakeholders, airspace sectors are also considered in the analysis, following in the case of Europe the current classification (EUROCONTROL, 2005).

Finally, the choice of exposed assets to be considered in the analysis accounts also for the socio-economic context. For example, the territorial context of an airport or a connection is relevant for the estimation of socio-economic vulnerability and impact. In addition, many population and productive activities rely on air traffic and are thus indirectly exposed to its disruption, and are therefore included in the analysis.

2. **Vulnerability assessment.** The objective of vulnerability analysis is to define indicators to measure the systemic vulnerability of air traffic network to tephra dispersal. As clearly demonstrated during the Eyjafjallajökull eruption in 2010, the European air traffic system is largely vulnerable to loss of functionality of its elements when exposed to volcanic ash. Impacts of ash clouds can occur very far from the source, and their magnitude depends on the relevance of the disrupted elements (Ceudech et al., 2011).
The first step is therefore to identify the strategic elements amongst those identified by the exposure analysis. The analysis of the network structure allows the main elements that are critical for the system as a whole to be recognized (Wegner and Marsh, 2007; Hustache et al., 2011; Wilkinson et al., 2011). This section presents the criteria and assumptions for the identification of the critical elements for the system.

    - The main assumption is that the higher the traffic of an airport, the higher its relevance and, consequently, the higher the vulnerability of the system to its potential disruption. Strategic airport hubs are identified in terms of passengers and goods transported. **Paper III** classifies all European airports according to traffic of passengers and freight during 2012 (EUROSTAT, 2013). All European airports are classified in order to identify the most important for the whole European area. The analysis is performed also for the North-Western Europe, expected to suffer impacts due to ash dispersal from Icelandic volcanoes according to the probabilistic hazard assessment results (Biass et al., 2014).

    - Similarly, the assumption is that the higher the traffic of passengers and freights on a given route, the higher its relevance and, consequently, the higher the vulnerability of the system to its potential disruption. **Paper III** classifies routes based on the average number of connections between each pair of European airports in 2012, identifying the main city pairs. In addition, it also classifies routes based on air traffic (passengers and freight) for each city pair, that is, for the main routes between a considered airport and its partners (Eurostat). This allows accounting the relevance of European routes for a selected sub-system constituted by the considered airport and its main European partners.

- Highly congested airspaces (i.e. those more relevant for the air traffic system) are identified based on the level of traffic in each airspace sector. **Paper III** identifies the strategic European airspace sectors based on the number of daily European flights in each sector. Traffic data correspond to the peak day of 2012 (29 June), under the assumption that this particular day is representative of high-traffic situations in Europe. Each airspace sector is assigned a vulnerability value according to the number of times per day the sector is crossed by flights at any FL. This analysis could also be performed with different datasets (i.e. peak days, projections, average values) and at different timescales.

- The main assumption is that socio-economic vulnerability of the air traffic system is proportional to the level of dependency of a territory on air transportation. The socio-economic vulnerability is high at areas that strongly rely on air traffic system, or in correspondence of special territorial conditions (e.g. islands). The vulnerability of air traffic network is low in case of high redundancy of the transportation network (e.g. in presence of other transportation infrastructures that can replace air traffic in case of disruption). Areas having low multi-modal accessibility are more vulnerable to the failure of one transportation mode due to the limited variety of alternative transportation modes. **Paper III** identifies the European regions that have a high dependency on air traffic combining four indicators: population, passengers and freight transported by air and multi-modal accessibility. In particular, multi-modal accessibility takes into account the presence/absence of alternative transport modes and their cost (Espon, 2003; Espon, 2013, p. 17). These indicators are combined on a cell-by-cell basis using GIS spatial analysis functions. The analysis is based on average yearly data for 2012, gathered from the Eurostat database (EUROSTAT, 2013). This simplified but novel approach poses the basis for including these aspects in long-term territorial risk management. All indicators are referred to the 2003 NUTS-2 regions (Nomenclature of Territorial Units for Statistics), a hierarchical system for dividing the economic territory of the EU for the application of regional policies.

Based on these considerations, vulnerability values are associated to the exposed elements, using a qualitative scale in order to allow a first-order comparison.

3. **Impact assessment.** Once the strategic elements and their relevance are identified, it is possible to assess the expected impacts produced by different eruptive scenarios based on hazard and vulnerability maps. Given the differences in the indicators of vulnerability, it is not possible to merge the different thematic vulnerability maps into a single map. Expected impacts are thus assessed separately for each single vulnerability feature.

   The combination of hazard and vulnerability results allows the expected impacts in case of occurrence of a considered scenario to be identified. **Paper III** proposes three methods for estimating long-term impacts of tephra dispersal on European air traffic:

   - Qualitative GIS-based visual overlap of hazard and vulnerability maps. The graphical overlap allows visual identification of the routes that have the highest probability of being disrupted for each eruptive scenario. Visual overlap can improve risk communication showing the spatial distribution of variables that contribute to the occurrence of disruptions (i.e. hazard, exposure and vulnerability).

   - GIS-based overlap of hazard and vulnerability information. This corresponds to a spatial analysis operation that, having converted the maps into raster format, calculates the impact as product of hazard and vulnerability on a cell-by-cell basis (similarly to Fig. 3.5). This analysis has been performed for Flight Information Regions (FIRs) associated to a constant value of vulnerability (as described in previous subsection) and covered by different values of hazard (contained in the hazard map). The impact value for the FIR is the maximum value encountered amongst the cells within its airspace. Impact maps allow identifying which airspaces would be impacted, and the spatial extent of impacts.

   - A third way of assessing impacts is calculating the expected disruption for given features, for example at given airports, based on average data on a given time interval (hourly, daily, yearly). For example, impact at given airports (i.e. movements disrupted, passengers and freight stranded) can be estimated by multiplying the persistence time for a given eruptive scenario by the hourly-averaged traffic (based on daily average data). The underlying assumption is that if the critical ash concentration is reached at any FL over an airport, all flight operations are disrupted. Examples for the airports of London Heathrow and Keflavík are presented in **Paper III**. This method could be based on critical thresholds in terms of arrival and persistence time (e.g. assuming a strong economic impact if the disruptions last more than 6 hours at a given airport).

Each of the above impact assessment methods focus on producing specific results, and could be used to support risk management strategies at different levels. In addition, these methods can be applied to any area for which a hazard and vulnerability assessment has been previously performed.

This work presents the first example of a vulnerability and impact assessment methodology of air traffic network in case of explosive volcanic eruptions. Results produced for the European air traffic system are presented in **Paper III**. Results of the analysis are vulnerability maps for the main analyzed features (airports, flights, airspace sectors, European regions) and impact maps for airspace sectors. Such maps put the basis for long-term aviation management and allow identifying areas that are likely to suffer impacts in case of occurrence of the considered eruption. Finally, based on long-term air traffic data, it is possible to quantify expected disruptions at relevant airports.
It is worth noticing that a full characterization of physical vulnerability is beyond the scope of our research, that is mainly focused on identifying the systemic vulnerability of air traffic system. Regarding physical vulnerability of elements, it is assumed that all exposed elements are equally vulnerable to the occurrence and overpassing of critical ash concentration values (section 3.2.1), following a common approach presented by Douglas (2007).

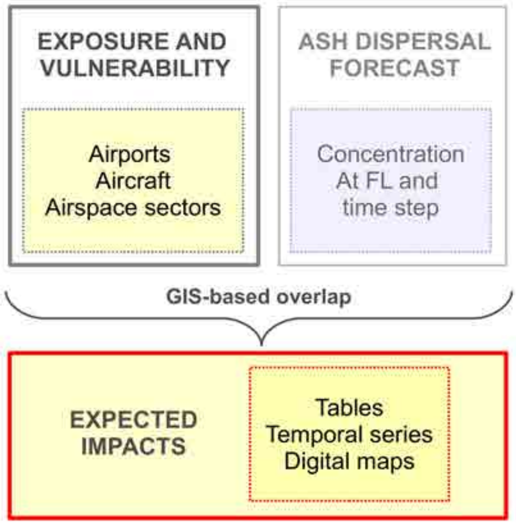

FIGURE 3.8: Short-term impact assessment methodology, constituted by exposure and vulnerability analysis (left) and ash dispersal forecast (right), whose outcomes are combined by a GIS-based overlap to estimate expected impacts (bottom).

3.2.3 Short-term impact assessment on air traffic network

This section presents a methodology for the short-term impact assessment of air traffic networks in case of explosive volcanic eruptions. Exposed elements are identified according to the methodology presented in the previous section. Given that short-term analysis is focused on the quasi-real-time estimation of impacts, a value of constant maximum vulnerability is traditionally associated to the exposed elements (Douglas, 2007).

The proper impact assessment consists essentially in a GIS-based overlap of ash concentration maps and air traffic features (Fig. 3.8) that allows identifying which ones may suffer disruptions. However, prior to these operation, an important task has to be performed: the pre-processing of input data (i.e. air traffic data and TTDM outputs). The aim of pre-processing is preparing the input data for the impact assessment.

The impact assessment methodology is automated into a GIS-based tool that performs all the steps of the impact assessment and estimates the impacts, producing outputs in different formats. The tool has been applied for assessing expected impacts in case of occurrence of explosive volcanic eruptions at 2 active Icelandic volcanoes (Scaini et al., 2011; **Paper IV**).

1. **Pre-processing of TTDM outputs.** Outputs from ash dispersal models contain values of ash concentration at discrete points and at regular time intervals, which typically range from 1 to 6 or 12 hours depending on the model configuration.

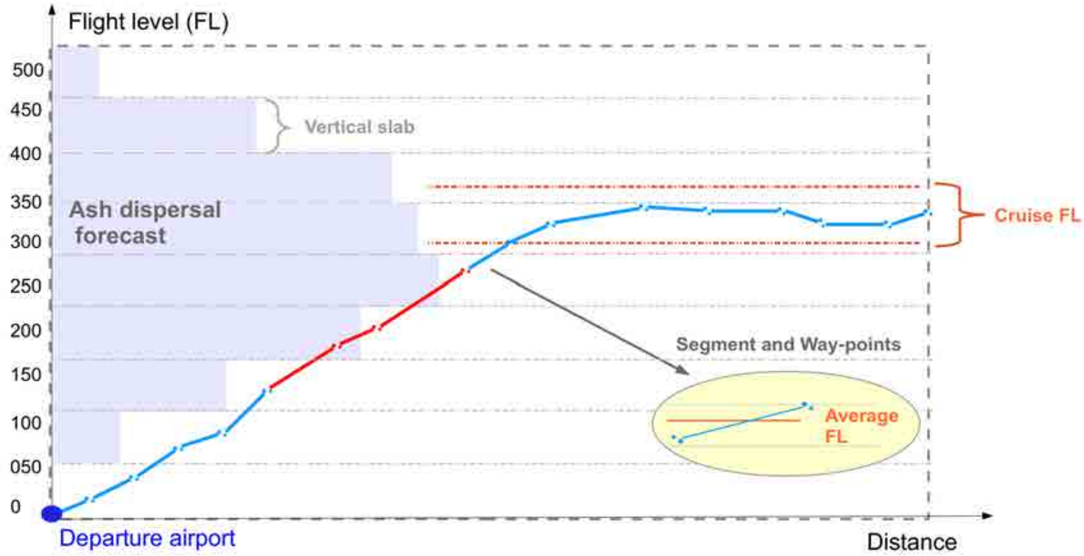

FIGURE 3.9: Spatial structure of data sources. Forecasted concentration values are interpolated at regular non-overlapping slabs, and each concentration threshold value defines a time-dependent contaminated volume (shaded in light blue). A flight trajectory is constituted by a series of segments, each with an average FL (bottom right zoom). The impacted segments are shown in red.

Normally, these points conform 2D regular longitude-latitude grids that contain values of concentration at discrete Flight Levels (FLs) or values of concentration vertically averaged across slabs (e.g. from surface to FL200, from FL200 to FL300, etc.). Hourly maps of ash concentration are extracted at given vertical levels, that correspond to contiguous intervals of Flight Levels (FLs), that is, non-overlapping slabs within which ash concentration is assumed constant along the vertical and for each time interval (Fig. 3.9).

The pre-processing operations allow accounting for temporal and spatial uncertainties related to the TTDM output through temporal and spatial buffers (Fig. 3.10). First, the "temporal buffer" creates a new contour map considering, for each spatial point, the maximum value of concentration between the current time and at previous/successive time steps (i.e. from $t - nt$ to $t + nt$, where n defines the extent of the temporal buffer). Then, a "spatial buffer" further increases the area of the polygon by a quantity that increases with time in order to reflect the loss of forecast accuracy with time. The user can configure both buffers depending on the degree of confidence on the forecasts.

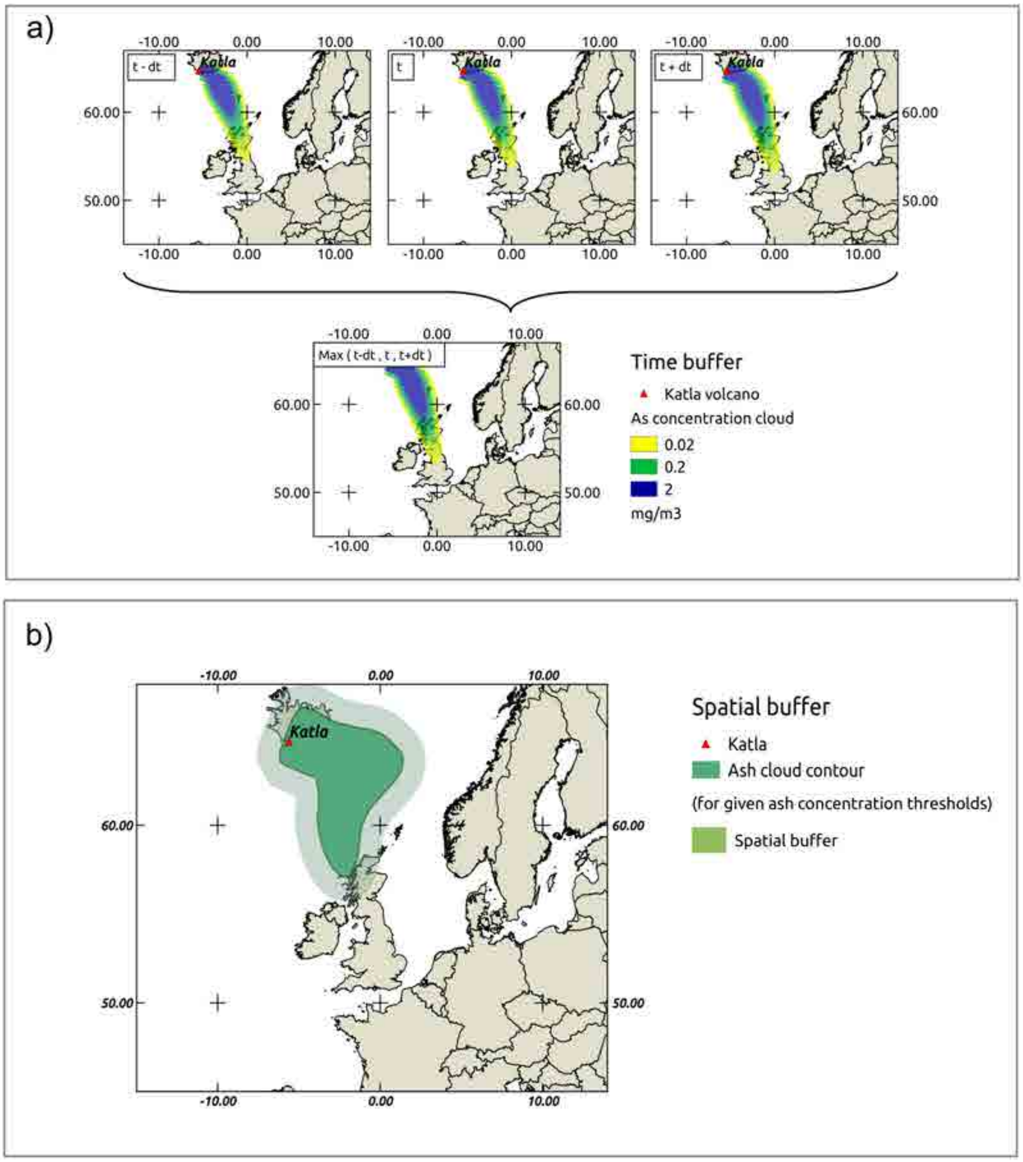

Figure 3.10: (a) A temporal buffer can be applied to the model outputs to account for time uncertainty in cloud location. For each vertical slab, concentration contours are compared with those of previous/successive time steps and a new map containing the maximum value for each cell is produced. (b) A spatial buffer can be applied to account for spatial uncertainty in cloud location. The buffer enlarges the contaminated region to an extent that increases with time. Both buffers can be switched on/off by the user and configured depending on the model level of uncertainty.

The pre-processing stage extracts automatically ash concentration values at discrete FLs, applies the temporal and spatial buffers and builds ash dispersal polygons. Each contour (one for each threshold) delineates an area in which ash concentration overpasses the corresponding threshold. Tephra dispersal forecasts may be stored in different formats, depending on the TTDM used. Currently, only

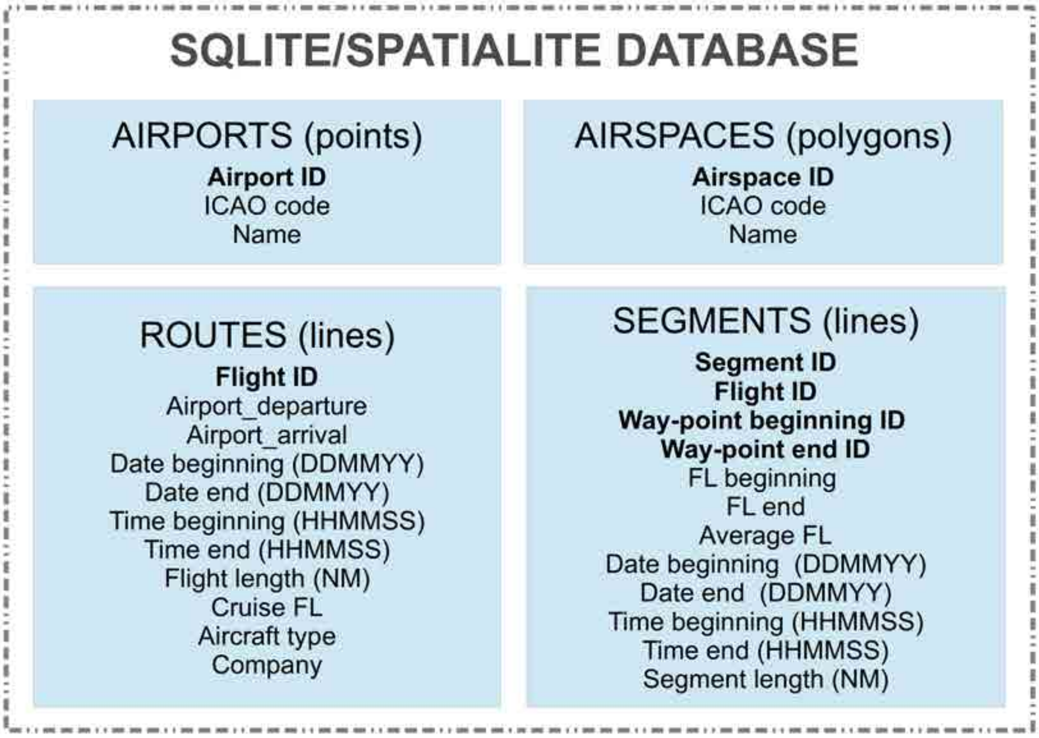

Figure 3.11: Structure of the spatial database that stores the air traffic elements (airports, airspaces, routes and segments). Each element is associated to an unique identifier (ID) and several attributes.

Fall3d model is supported, but this can be easily resolved by modifying the script to import data at different FLs and time intervals.

2. **Air traffic data management.** The short-term impact assessment methodology relies on a DBMS to support automated queries at a given temporal resolution. This research proposes and adopts a structure (i.e. a template) for storing air traffic data that are taken as input for the short-term impact assessment (Fig. 3.11). Air traffic data are automatically imported into the template and interfaced with the GIS to perform impact assessment operations. Each entity is associated with the unique identifier (ID) of the original air traffic database.
This template is the first database produced for the purpose of assessing impacts of volcanic ash dispersal on air traffic during volcanic eruptions. Besides its function in storing air traffic data (Fig. 3.11), the DBMS also contains also ash concentration data, and stores the results of the impact assessment analysis. The impact assessment methodology has been applied to the European case-study (Scaini et al. (2011); **Paper IV**) using air traffic data from EUROCONTROL Demand Data Repository (DDR, EUROCONTROL, 2010). This database contains the last filed

flight plans, constituted by way-points and connection segments. The analysis of Scaini et al. (2011) is based on a representative day for April air traffic in Europe in order to reproduce the 2010 aviation breakdown, while for **Paper IV** a day that corresponds to worst-case meteorological conditions has been selected.

All the pre-processing and data management operations are automatically performed by scripts that act as an interface between different tools (GIS, libraries, DBMS). The methodology for extracting ash concentration and air traffic data from the respective data sources is described in detail in **Paper IV**. Currently, only the EUROCONTROL database used in Scaini et al. (2011) and **Paper IV** is supported. A similar procedure could be applied to other data sources (different TTDM outputs and air traffic datasets), increasing the usability of the tool for different end-users. Air traffic could be available in different formats depending on the used software package. Thus, air traffic data are not necessarily in the same format that the tool can process. This can be easily resolved by writing a dedicated script to import data in the required format.

3. **Impact assessment.** This section describes the methodology that allows identifying features (airports, routes, sectors) that are expected to be affected by volcanic ash dispersal. A first version of the impact assessment methodology has been presented by Scaini et al. (2011) and it has subsequently improved it into a new version (**Paper IV**).

   Impact and disruptions are defined as situations in which the elements at stake may suffer a loss of functionality. This may be due to the presence of volcanic ash in critical concentrations (i.e., overpassing a given ash concentration threshold) or to indirect effects (e.g. the disruption of an airport can influence airborne operations). Similarly to the long-term methodology, in absence of physical vulnerability characterization for the exposed elements, it is assumed that all elements are equally vulnerable to critical ash concentration values. The analysis is performed at each time step of the analysis, that can vary depending on the temporal resolution of data and, in particular, on the frequency at which ash concentration is estimated by the TTDM model.

   - Airports. Impact assessment of airports is based on identifying airports expected to have critical ash concentration in the close airspace. Given that most of take-off, landing and approach operations occurr at lower FLs, operations at airports having critical ash concentration at any of these FLs are considered as potentially disrupted. In order to account for the spatial extent of airports, a radial buffer is applied to the point features, at an extent that can be selected by the user. The buffer accounts for the spatial extent of airports control areas and may be in future replaced by other spatial units, depending on forthcoming regulations.

- Routes. Regarding routes, the methodology refers to impacts on flights as possible cancellations or modifications (rerouting, delay) that may be operated by the stakeholder responsible of taking the final decision on whether to fly or not through ash-contaminated airspace. Flights expected to be impacted are identified distinguishing two main cases: flights can be impacted due to the expected closure of the arrival/departure airport or to the presence of ash clouds along their path. This research also proposes a new methodology for impact assessment based on the overall amount of ash ingested by an aircraft over his path. In addition, Scaini et al. (2011) (Appendix B) show that, for intra-European flights, upper FLs are much less congested than lower FLs. Also, in case of long-lasting eruptions with low eruptive columns, upper FLs are in some cases free of ash. This suggests that a flight disrupted at requested FL may be operated at upper FLs performing a rerouting procedure. In order to support such operation, the methodology allows identifying routes impacted at low FLs not expected to intersect the ash cloud at upper FLs.

- Airspace sectors. If airspaces are affected by critical ash concentration they are expected to be impacted. The percentage of sector affected by ash can support a qualitative impact classification. **Paper IV**, for example, a high impact on airspaces is associated to more than 50% of the sector surface covered by ash. If the are affected is lower than 10% of the total area, impact on airspace is considered low. These criteria have been chosen according to personal experience and practical considerations, and may be changed in the future according to end-user requirements.

  Finally, given that airspaces have vertical extension and, in terms of ATM, are considered as a single spatial feature, a final assessment is produced considering as potentially impacted all sectors where ash is forecasted at any of the considered FLs.

The impact assessment methodology is then automated into a GIS-based tool that performs all the steps automatically, producing outputs in different formats.

4. **The GIS-based tool.** A first version of the tool was presented by Scaini et al. (2011) and then improved in a new version (**Paper IV**). The tool takes as inputs air traffic data and TTDM outputs and applies the methodology described previously and showed in Figure 3.12.
   The tool is constituted by several programs that post-process input data, overlap TTDM outputs and air traffic data and estimate expected impacts. The user introduces parameters for the analysis, such as the temporal resolution for the impact assessment (Table 3.1). The tool automatically produces impact assessment output in different formats. Graphical output is exported in two formats: shapefile, that can be visualized through GIS, or kml files, for Google Earth. The tool can also export the temporal series of impacts, for example the number of flights canceled over time, allowing the user to identify expected impact peaks. Examples of outputs are presented in Scaini et al. (2011) and **Paper IV**. Thus, the tool favors the visualization of TTDMs outputs and impact assessment results, recognized to be crucial in order to improve the aviation management during crises.
   The tool runs under Unix/Linux/Mac OX systems using shell scripting and needs the installation of some software packages (GIS, DMBS and some processing libraries), all open source. Details are available in **Paper IV**.

This section presents the first impact assessment methodology specifically designed to identify expected impacts of explosive eruptions on air traffic network. In addition, the GIS-based tool allows the end-user to implement new spatial analyses not available with existing tools in an automated and flexible way.
Results of its application can be found in Scaini et al. (2011) and **Paper IV**. These works estimate expected impacts in case of occurrence of eruptive scenarios at Eyjafjallajökull and Katla volcanoes. Results are presented in Chapter 4 and provide useful insights for the definition of response strategies in case of explosive volcanic eruptions in Europe. Finally, the main caveats of the methodology and advantages and limitations of the tool are discussed in Chapter 5.

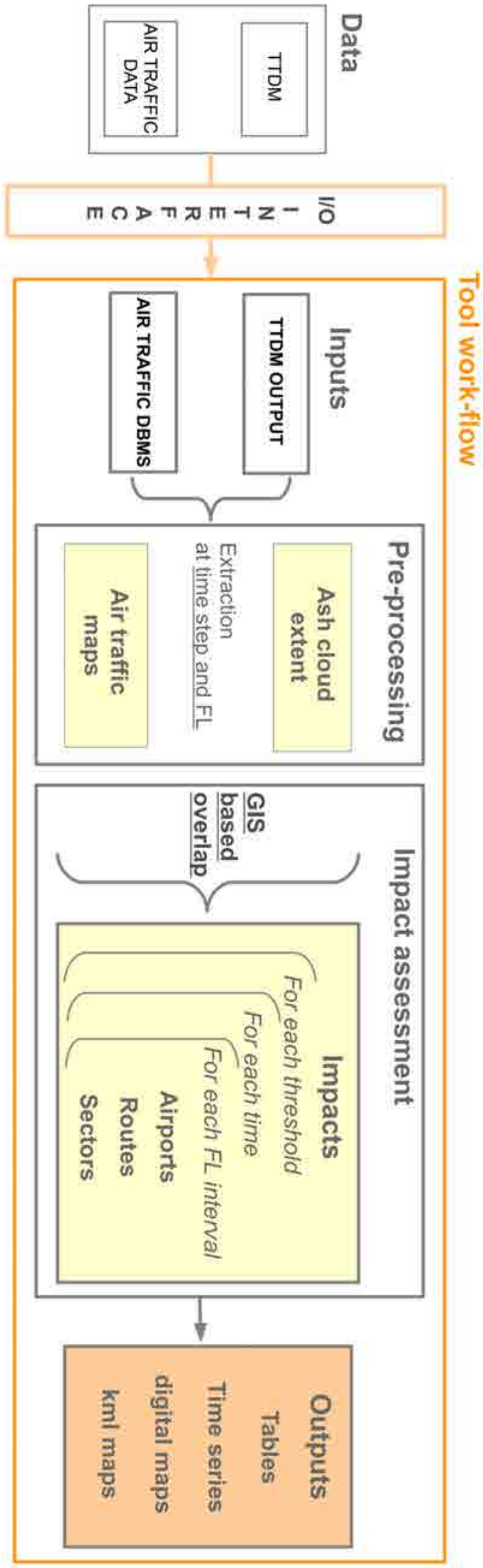

FIGURE 3.12: Workflow of the GIS-based tool. Input data (left) are pre-processed and imported into the GIS engine, which performs the overlap and produces impact assessment results in different formats (right).

Table 3.1: Input parameters of the GIS-based tool for automated impact assessment

GROUP	PARAMETER	DESCRIPTION	UNIT/TYPE
General parameters	eruption date	date of eruption start	YYYY-MM-DD
	time interval	Time interval for analysis	hours
	eruption start	eruption starting hours	Multiples of DT (hours after 00 UTC)
	run end	hours after eruption start	Multiples of DT (hours after 00 UTC)
Paths	Home path	home path for writing results	string
	Data path	Path to original database	string
	Hazard path	Path to forecast results	string
	Out path	Path to output folder	string
	Source path	Path to source code	string
Input data	database types	air traffic database used	Name
	Tables type	format to import/export data from database	format (ex. csv)
	model type	TTDM used	Model name
	output type	format of modeling output	Format (e.g. netCDF)
Grass GIS	data path	path to grass location	string
	location	name of grass location	Folder name
	mapset	name of grass mapset	Folder name
	SQL path	path to SQLite database	string
Database filtering	company	Filter data by company	Y/N
	company code	company code for filtering	Company code (table attached)
	departure airports	filter data by departure airport	Y/N
	departure airport code	departure airport code for filtering	ICAO airport code
	arrival airport	filter data by arrival airport	Y/N
	arrival airport code	arrival airport code for filtering	ICAO airport code
	City pair	filter data by city pair	Y/N
Uncertainties	airport buffer	Airport spatial buffer	decimal degrees
	FL buffer	FL vertical distance for extraction	FL units
	time buffer	ash cloud time buffer	multiple of DT
	ash cloud buffer	ash cloud spatial buffer	decimal degrees
	Value for increasing buffer	Increasement of spatial buffer	multiple of time interval
Rerouting	Rerouting analysis	if you want to perform the rerouting analysis	Y/N

3.3 Communication during explosive volcanic eruptions

3.3.1 Motivation

The 2010 Eyjafjallajökull eruption caused unprecedented disruptions of air traffic operations in Europe and highlighted major weaknesses of the scientific and operational knowledge (Bonadonna et al., 2011a; Bolić and Sivčev, 2011). In particular, communication and information flow between the actors was identified as a major concern, and its improvement is still an open issue (Bonadonna et al., 2011a; Bonadonna et al., 2013). Both low risk perception during "peace time" and complexity of actors and relationships implemented during emergencies contribute in incrementing the vulnerability of the aviation system (Bolić and Sivčev, 2011), that may be reduced increasing preparedness and response capability of stakeholders.

Actors involved in aviation management during explosive eruptions are: volcanologists, atmospheric ash dispersal modelers, meteorological offices, aviation and airline managers, pilots, air traffic controllers and national authorities. Since 2010, stakeholders involved in civil aviation management are taking into higher consideration volcanic eruptions and subsequent air traffic disruptions in their risk management plans. Moreover, many sectors indirectly impacted by aviation disruptions are now interested in developing strategies to lower socio-economic impacts (Jones and Bolivar, 2011). Thus, the range of involved actors is being enlarged to include representatives of activities and institutions (local/regional authorities, productive activities, insurance companies, citizen organizations, service providers), which should be considered in a comprehensive impact assessment analysis.

However, there are no comparative studies on the opinion of specific groups (e.g. modelers and aviation managers). In addition, due to the complexity and multidisciplinary nature of the topic and the wide spectrum of productive sectors impacted, the number of involved actors is growing, and involved stakeholders are fragmented and do not constitute a proper "community". Moreover, most on-going scientific and technical developments are mainly focused on specific aspects that concern homogeneous groups (e.g., modelers or aviation managers), often with little transversal interaction.

This analysis aims at identifying the relationships between many actors involved in aviation management and their priorities in order to improve in the information flow amongst them. An anonymous on-line survey was performed in order to identify the

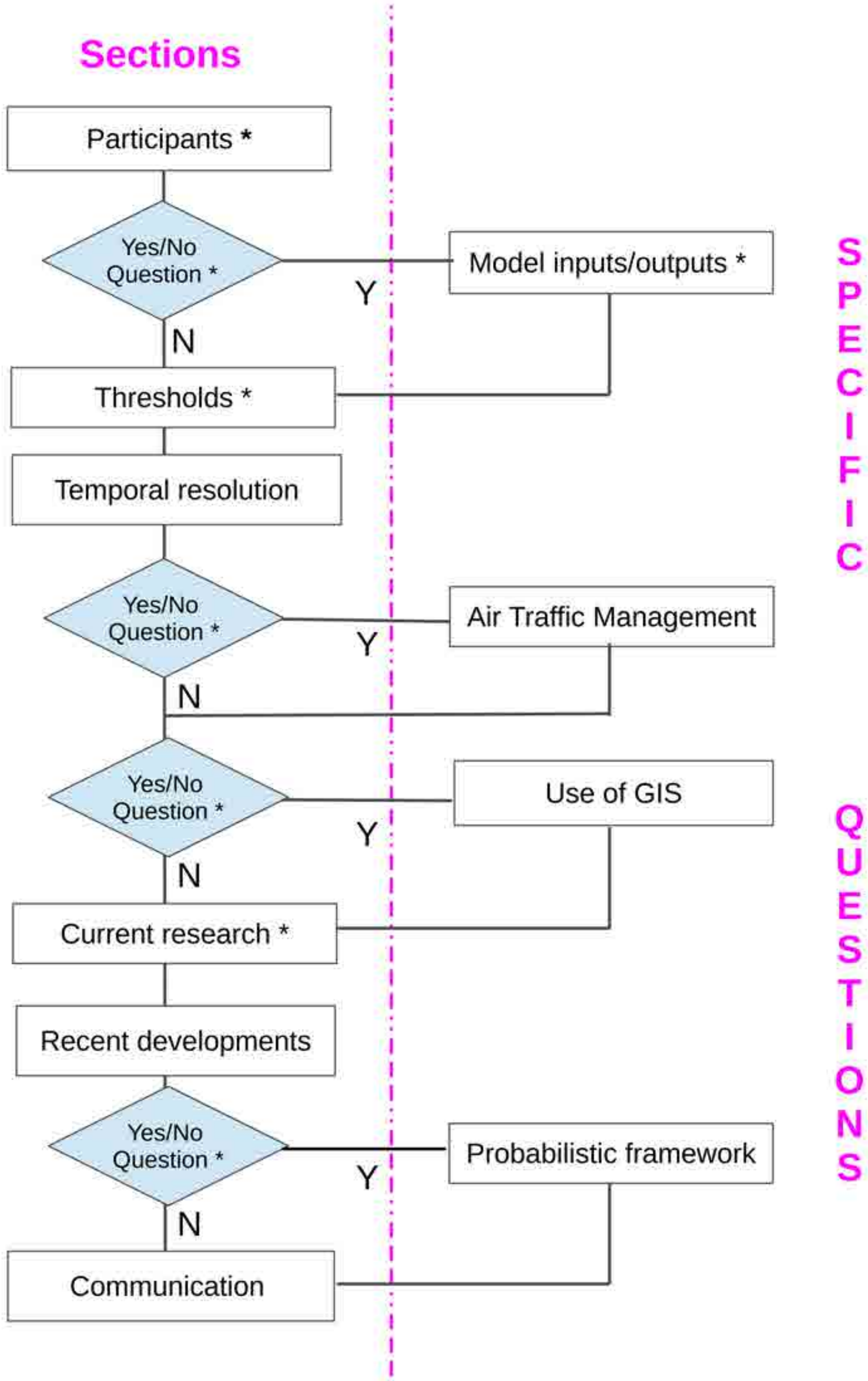

Figure 3.13: Flow chart of the survey, constituted by 10 thematic sections, containing different question focused on specific groups of respondents (right).

needs of the stakeholders. Furthermore, the survey intends to obtain participants' opinion on the outcomes of this PhD research, and in particular on the GIS-based tool to support aviation management during volcanic eruptions.

3.3.2 The web-based survey

The web-based survey of the stakeholders was been performed through an anonymous on-line questionnaire. Fig. 3.13 shows the structure of the survey. Sections contain mandatory questions are signalized by the symbol * in the figure and in the full-text survey (attached, Appendix C). Participants were classified into 4 homogeneous groups in order to identify the needs of each group and underline the main differences: aviation managers and employees, modelers and field scientists and other stakeholders.

The survey questions are focused on the following topics:

- Participants
- Tephra Transport and Dispersal Models (TTDMs)
- Ash Concentration Thresholds
- Forecast Temporal Resolution
- Air Traffic Management (ATM)
- Use of GIS
- Current Research on Impact Assessment
- Recent Developments
- Probabilistic Forecast Framework
- Communication

Results provide useful insights for the development of strategies to support policy-makers in the aviation sector during such events and give a first-order identification of end-user requirements for the development of our GIS-based tool. Chapter 4 collects the results of the survey, and present the main findings.

Chapter 4

Results

4.1 Tephra dispersal hazard assessment for civil aviation purposes

This PhD research produced probabilistic tephra dispersal hazard maps based on quantitative ash concentration thresholds, by applying the strategies presented in Section 3.1. Hazard maps were produced for two active volcanoes: Concepción (Nicaragua) and Popocatépetl (Mexico), presented respectively in **Paper I** and **Paper II**. Tephra dispersal hazard maps were also produced for specific time periods (i.e. wet/dry season) in order to underline seasonal patterns.

This research has also contributed to the co-authored work of Sulpizio et al. (2012), which presents probabilistic tephra dispersal hazard maps for Vesuvius (Italy) and introduce the first maps of persistence. This research has also contributed to Biass et al. (2014), which performs a multi-scale hazard assessment for 4 active Icelandic volcanoes. Having identified the eruptive scenarios for four active volcanoes in Iceland, Biass et al. (2014) present average persistence and arrival time maps at different FLs and at points of interest (i.e. airports). The authors also calculate standard deviation of these variables in order to quantify uncertainties related to modeling results. The work of Biass et al. (2014) is complemented by the companion paper included in this compendium (**Paper IV**).

Given the multi-hazard character of explosive volcanism, tephra fallout hazard maps for the considered volcanoes were also produced. These maps allow identifying the airports

that are expected to be impacted by tephra fallout. Although such impacts occur only at close distance from the volcano, the closure of airports can indirectly impact the air traffic network. In addition, the analysis of expected impacts of ash fallout on the infrastructural and socio-economic system can provide useful insights for estimating the socio-economic impacts of air traffic disruptions.
This section presents the results of the mentioned works in chronological order based on the publication date.

4.1.1 Hazard assessment at Concepción, Nicaragua

Concepción volcano in Ometepe Island, Nicaragua, is a highly active volcano with a rich historical record of explosive eruptions. Tephra fallout from Concepción jeopardizes the surrounding populations, whereas volcanic ash clouds threat aerial navigation at a regional level. The assessment of these hazards is thus important for territorial planning and adoption of mitigation measures.
Probabilistic hazard maps for Concepción volcano were computed considering three different eruptive scenarios based on past reference events. Following the work of Delgado-Granados et al. (2006), three different eruptive scenarios for Concepción volcano were identified for low, medium and high magnitude eruptions (See **Paper I** for details). Each scenario is associated to a reference eruption in the eruptive record of Concepción volcano, and to a Volcanic Explosivity Index (VEI, Newhall and Self, 2008):

- Low Magnitude Scenario (LMS) considers an eruption similar to the 2009–2011 events. The scenario is characterized by a short, very small intensity eruption (VEI$\approx$ 1) with gas ejection and few emission of tephra, as has been occurring since the 1977 eruption. This kind of event has the higher probability of short-term occurrence. The expected consequences of the LMS are low to moderate damages to proximal crops, minor damages to structures, and partial disruption of traffic in the island.

- Medium Magnitude Scenario (MMS) considers an eruption similar to the 1977 event documented by Delgado-Granados et al. (2006). This scenario is characterized by a short-duration Strombolian eruption of moderate intensity (VEI$\approx$ 2–3) with development of a sustained eruptive column and considerable emission of

Table 4.1: Ranges for main eruptive parameters considered in the tephra hazard assessment for Popocatépetl volcano. A Gaussian PDF peaking at average value is assumed. Values of MER are obtained from column height using the BPT relationships.

Parameter		LMS	MMS	HMS
Column height (km)	Min	2	3	12
	Average	2	5	20
	Max	2	7	28
MER (kg/s)	Min	10^4	10^5	10^6
	Average	10^4	$5 * 10^5$	10^7
	Max	10^4	10^6	10^8
Duration (h)	Min	1	0.5	6
	Average	1	1.5	30
	Max	1	2.5	52
Mean particle size (ϕ)	Min	1	2	2
	Average	1	1	1
	Max	1	0	0

tephra. Impacts are expected not only in the island, but also across the continental shore of the Nicaragua Lake.

- High Magnitude Scenario (HMS) considers an eruption similar to the 2720 B.P. "Tierra Blanca" event, which marked the end of the first building phase of the volcanic edifice (Borgia and Van Wyk de Vries, 2003). This scenario is characterized by a sub-Plinian to Plinian eruption (VEI$\approx$ 4) with a vigorous sustained column lasting from several hours to few days.

These three scenarios correspond to the most significant types of events expected for Concepción volcano and allow performing a general and coherent hazard assessment. Table 4.1 shows the ranges of main eruptive parameters for the three eruptive scenarios defined.

The modeling strategy adopted for the hazard assessment relies on the methodologies presented in section 3.1.1. The Eruptive Source Parameters (ESPs) of the reference events are based on previous geological analyses, and uncertainties in the definition of the scenarios are accounted trough the use of Probability Density Functions (PDFs). A representative meteorological dataset was created for each scenario by running the WRF-ARW mesoscale meteorological model over a Typical Meteorological Year (TMY),

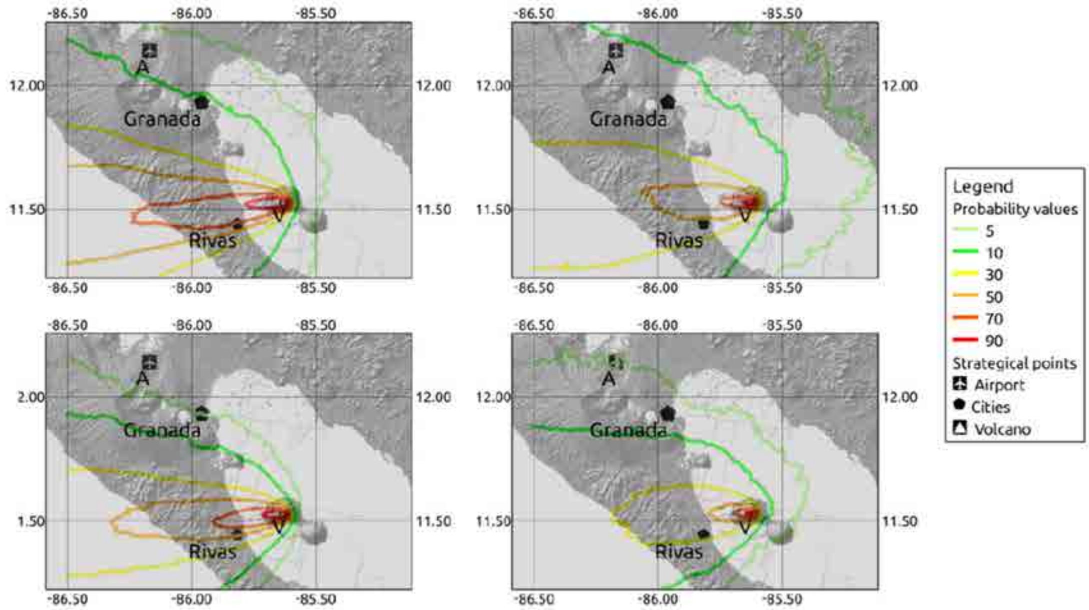

FIGURE 4.1: Probabilistic hazard maps of tephra dispersal at FL050 (left) and 150 (right) for critical concentration values of 0.2 (top) and 2 (bottom) mg/m^3, in case of occurrence of a medium-magnitude eruptive scenario at Concepción volcano.

defined in terms of wind speed and direction at a given atmospheric height (different for each scenario).

Tephra transport and deposition under different eruption and wind conditions was modelled using the FALL3D dispersion model. For MMS and HMS, hazard maps were computed performing two simulations per day (eruptions assumed to start at 06:00 and 18:00 LT) during the whole TMY. In contrast, for the LMS a full hazard assessment was not performed, as few simulations already showed that the consequences of this event cause only minor effects. For each scenario, simulations were combined to build probabilistic hazard maps for critical values of tephra load and for threshold values of airborne ash concentration at relevant Flight Levels (FLs).

Results are probabilistic hazard maps for tephra fallout and dispersal, produced at local and regional scale. Figures 4.1 and 4.2 show airborne ash concentration hazard maps for MMS and HMS at FL050 (left) and FL150 (right). Contours give the probability to achieve values of 0.2 (top) and 2 (bottom) mg/m^3 respectively.

Fig. 4.3 shows probabilistic hazard maps for ash fallout for HMS. For each eruptive scenario, the probability (in %) of exceeding thresholds of tephra ground load and airborne ash concentrations at relevant locations (e.g. main towns and airports) was also calculated. Such maps are useful to identify the expected impacts for each eruption type. Main results can be summarized as follows:

- LMS (2 km mean column height, VEI≈ 1) poses little threat on communities and air traffic. Expected impacts of fallout consist of minor road traffic disruption in areas close to the volcano. No substantial tephra accumulation is expected in the main villages of Ometepe. Critical airborne ash concentration values are also very localized and have a short duration.

- For the MMS (5 km mean column height, VEI≈ 2–3) results indicate that road traffic disruption can be expected over the whole Ometepe Island and in the mainland, with effects extending across the provinces of Rivas and Granada. However, the probability of tephra fallout is very low at Managua and at the international airport (5%). Tephra deposition could damage crops and pastures and affect the mainland province of Rivas, where agriculture is the main economical activity. Results suggest that collapse of buildings and structures would be very localized in the volcano flanks, affecting mostly sparse buildings. However, it is worth to mention that MMS threats large parts of the island, not because of copious tephra fallout, but by remobilization of deposits emplaced at the volcano flanks during

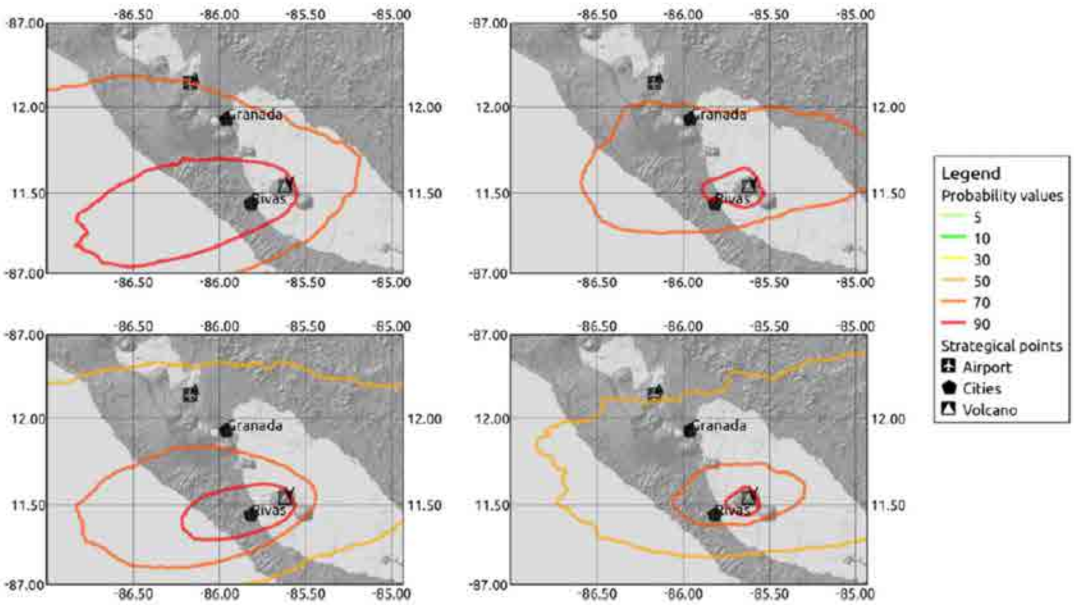

Figure 4.2: Probabilistic hazard maps of tephra dispersal at FL050 (left) and 150 (right) for critical concentration values of 0.2 (top) and 2 (bottom) mg/m^3, in case of occurrence of a high-magnitude eruptive scenario at Concepción volcano.

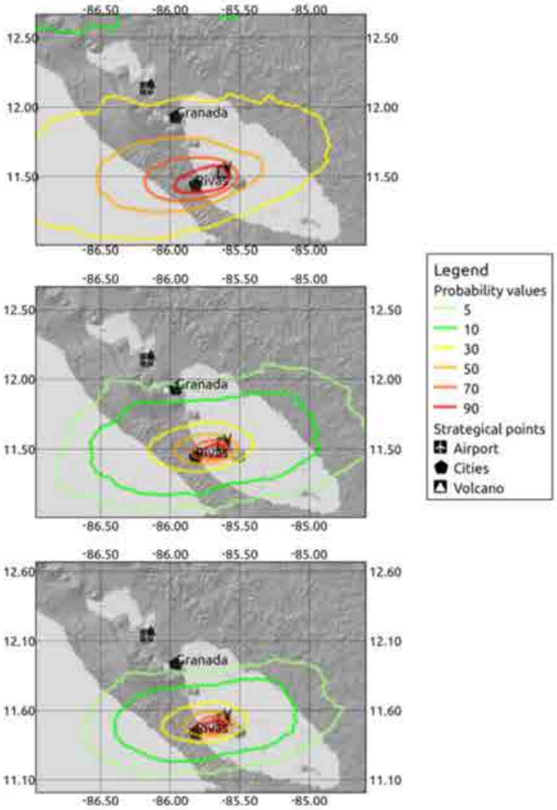

FIGURE 4.3: Probabilistic hazard maps of ash fallout in case of occurrence of a MHS scenario at Concepción volcano. Contours give the probability to achieve values of 1 (top), 50 (middle), and 100 (bottom) kg/m^2 respectively

eventual strong rain episodes. For this scenario, very weak seasonal influence was found.

- HMS (20 km mean column height, VEI$\approx$ 4) is likely to produce generalized disruption of ground transportation systems in the whole central part of Nicaragua. This situation could easily lead to a north–south partition of the country, with consequent damages to the main economical activities, including agriculture and commerce. Emergency response operations should be prepared to cope with this situation. Collapse of buildings and structures would be massive, especially in the island of Ometepe and in the Rivas province and, to a lesser extent, also in Granada and Managua. For this scenario there is a strong seasonal influence caused by the variability of the prevailing winds in the upper atmosphere.

Managua International airport is the only international airport in Nicaragua and one of the busiest in Central America. This work assessed at first-level the expected impacts of each scenario on air traffic. The probability of declaring a no-fly zone (airborne ash concentration of 0.2 mg/m^3) over most of the Nicaraguan airspace is not negligible for MMS (up to 5%) and very high for HMS (up to 57%). For MMS, the airspace above Rivas and Granada should probably be closed and the functionality of the Managua airport may be reduced due to ash at low FL impeding landing and take-off operations. However, ash clouds are typically dispersed in hours and, in practical terms, the crisis could be managed with flight re-routing and reallocation. In contrast, the airspace above Managua International Airport presents a high probability of affectation during the HMS, which may cause serious disruption of the National and Regional air transportation system.

Hazard maps developed for Concepción volcano underline the threat of explosive volcanic eruption to the exposed areas, and point out the importance of adopting specific mitigation measures for vulnerability reduction. These maps are thus important for the definition of a strategic plan for sustainable land development and to improve medium and long-term risk assessment in this region.

4.1.2 Hazard assessment at Vesuvius, Italy

This co-authored work assessed the hazard for civil aviation posed by volcanic ash from a potential violent Strombolian eruption of Somma-Vesuvius. In case of unrest at Somma-Vesuvius volcano, according to previous geological studies (Arrighi et al., 2001; Cioni et al., 2008) there is a high probability (38 %) for the eruption to be violent Strombolian (Neri et al., 2008). This type of activity has been in fact common in the most recent period of activity (between AD 1631 and 1944). The selected eruptive scenario represents the most likely volcanic activity at Vesuvius. The definition of the violent Strombolian eruption scenario is explained in detail in Sulpizio et al. (2012). Table 4.2 summarizes the input parameters defined for the modeled scenario.

Given that violent Strombolian eruptions typically last longer than higher-magnitude events (from 3 to 7 days for the climactic phases), they are likely to cause prolonged air traffic disruptions. Such impacts are likely to reach large distances due to the high amount of fine ash typically produced during Vesuvius eruptive activity.

In this work, similarly to **Paper I**, probabilistic hazard maps were produced at two flight levels (FL050 and FL300) and for two concentration thresholds (0.2 and 2 mg/m^3) that show the probability (in %) to exceed the threshold at any time during a violent

Table 4.2: Eruptive scenarios considered in the tephra hazard assessment for Somma-Vesuvius volcano, Italy (Modified from Sulpizio et al., 2012.

	Mean	Minimum	Maximum	Distribution
Eruption starting time	-	1	3	Uniform
Eruption duration (days)	5	3	7	Beta
Total mass ($*10^{11}$ kg)	2.5	1	5	Beta
Mean grain size coarse mode (ϕ)	-1	-2	0	Beta
Mean grain size fine mode (ϕ)	3	2	4	Beta
Dispersion grain size (ϕ)	2	1	3	Beta
Density coarse mode (kg/m^3)	1.600	1.400	1.800	Beta
Density fine mode (kg/m^3)	2.700	2.600	2.800	Beta
Sphericity	0.92	0.90	0.94	Beta
% Aggregates	30	10	50	Beta
Column height (km)	6	3	9	Beta
Suzuki coefficient A	4	3	5	Beta

Strombolian eruption at Somma Vesuvius. In addition, this work presented the first example of persistence time maps for ash dispersal (Fig. 4.4). Finally, the seasonal influence on hazard assessment results was assessed with seasonal maps.

Results show that the occurrence of the considered eruptions at Vesuvius may affect air traffic over the Central and Eastern Mediterranean area, and in particular Southern Italy, Greece and the Balkans. Aerial corridors passing over Southern Italy, South Balkans, Greece and Northern Turkey have medium–high probability of being affected by ash concentrations exceeding 0.2 mg/m^3. Most of Italy, Central–Eastern Europe, Turkey, part of North Africa and the Middle East are within the >10 % probability contours.

Persistence time (Fig. 4.4) reaches 10–15 % of the eruption duration in a large area that extends from the Western Mediterranean to Central Turkey, including Italy, part of Central Europe and part of North Africa. It means that, in case of an eruption lasting 7 days, air traffic corridors within that area would be affected for an average period between 17 and 25 h. Persistence time of more than 25 % of eruption duration affects only

Southern Italy, causing operational problems only for domestic aerial corridors (more than 42 h for a 7-day eruption). The no-fly condition (threshold of 2 mg/m^3) has a limited impact on air traffic corridors, with probability in excess of 10 % encompassing only Southern Italy, Central-Southern Balkans and Northern Greece.

Persistence is also relatively low, with values between 10 and 15 % that affect only Southern Italy and the 1 % area that encompasses Central–Southern Italy, the Balkans and Northern Greece. Medium–low persistence will only cause the disruption of domestic aerial corridors over Southern Italy, allowing the long-range international flights to reroute their tracks over the Western Mediterranean or Balkans. Disruption of air traffic corridors over a large area including Balkans and Greece would be limited to a few hours, and may cause some disturbance to air traffic over the Central Mediterranean and Eastern Europe.

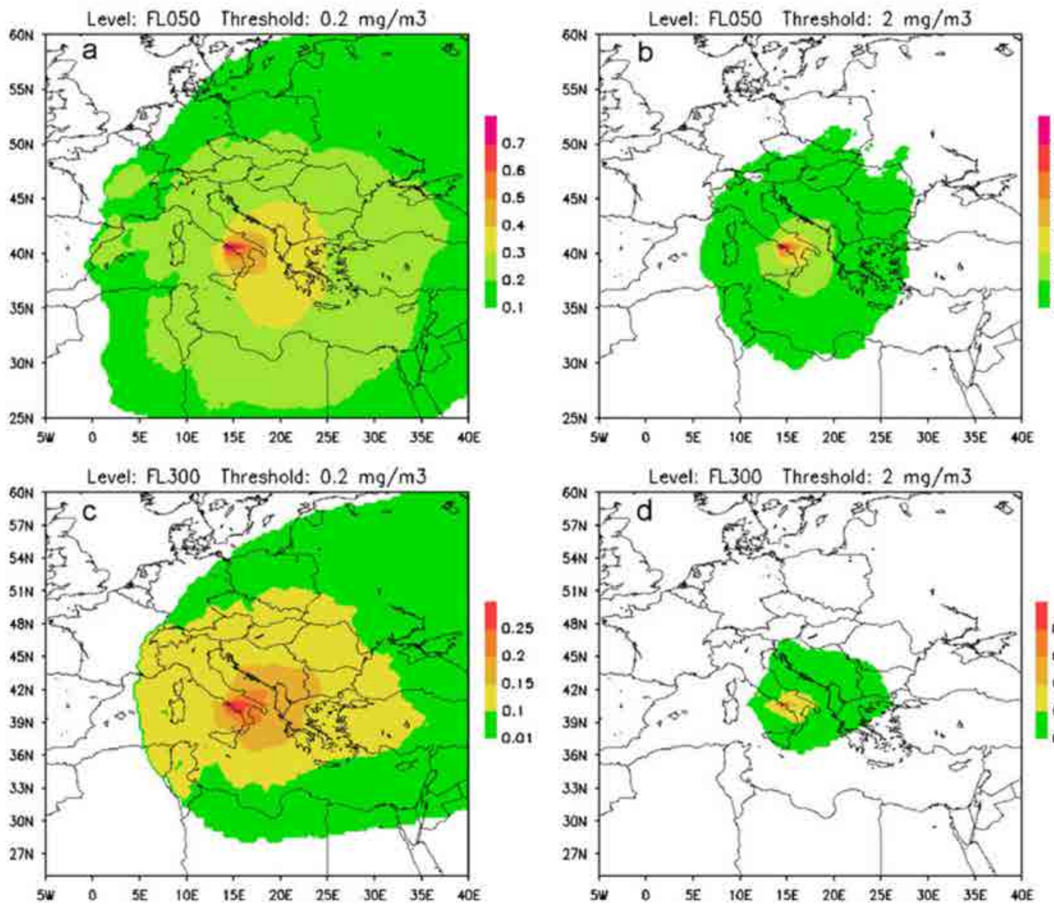

FIGURE 4.4: Persistence of given ash concentration values (0.2 and 2 mg/m^3, left and right respectively) at two flight levels (FL050 and FL300, top and bottom respectively), in case of occurrence of the selected eruptive scenario. Persistence is defined as the percentage of eruption duration (3-7 days) in which a concentration threshold is exceeded

The comparison with high-magnitude but shorter explosive volcanic events at Vesuvius (Folch and Sulpizio, 2010) shows that, although a Plinian eruption such as the one modeled by Folch and Sulpizio (2010) is likely to affect a larger area, the persistence of ash might be longer in the case of less-intense eruptions. In fact, the transit times of the ash clouds are limited to a few hours for the Subplinian eruption, but during the violent Strombolian the persistence can be in the order of several hours to few days. It follows that high-intensity eruptions can provoke disruption to air traffic over larger areas but for shorter times than lower intensity, long-lasting eruptions.
The hazard maps produced by Sulpizio et al. (2012) assess the potential impacts of a violent Strombolian eruption at Somma-Vesuvius to civil aviation over the Central Mediterranean area and East Europe. These results point out that even low intensity explosive eruptions at Vesuvius can have long-range consequences for aviation.

4.1.3 Hazard assessment at Popocatépetl, Mexico

Popocatépetl volcano is one of Mexico's most active volcanoes. Its activity can threaten a densely populated area that includes Mexico City, having by more than 20 million inhabitants. The destructive potential of this volcano is demonstrated by its historical eruptive activity, which has been characterized by recurrent Plinian eruptions of large magnitude, the last two of which destroyed human settlements in pre-Hispanic times. Popocatépetl's reawakening in 1994 produced a crisis that culminated with the evacuation of two villages on the North-eastern flank of the volcano. Shortly after, a monitoring system was implemented, and a civil protection contingency plan was defined based on a hazard assessment.
The current volcanic hazard map considers the potential occurrence of different volcanic phenomena, including pyroclastic density currents and lahars (a type of debris flow composed of volcanogenic pyroclastic material). However, no quantitative assessment of the tephra hazard, especially related to atmospheric dispersal, existed. Given the high number of important airports in the surroundings of Popocatépetl volcano and considering the potential threat posed to civil aviation in Mexico and adjacent regions in case of a Plinian eruption, a hazard assessment for tephra dispersal is required. **Paper II** presents the first probabilistic tephra dispersal hazard assessment for Popocatépetl volcano.
The reference eruption considered for defining the eruptive scenario is the Ochre Pumice

Table 4.3: Ranges for main eruptive parameters considered in the tephra hazard assessment for Popocatépetl volcano.

	Mean	Minimum	Maximum
Column height (km)	30.0	27.5	32.5
Eruption duration (h)	3.75	2.25	5.25
Mean grain size (ϕ)	4.00	2.25	5.75

eruption (OP, Arana-Salinas et al. 2010), selected as a possible Plinian eruption scenario because it represents one of the best-studied Holocene eruptions of this volcano and because, according to Mendoza-Rosas and De la Cruz-Reyna (2008), the probability of occurrence of at least one eruption exceeding a VEI of 4 (i.e., a magnitude similar to that of the Ochre Pumice eruption), over a period of 100 years is 10% and over 500 years is 43%.

Tephra dispersal was simulated using the FALL3D model. ESPs were constrained through an inversion method (see **Paper II** for details) The estimates of volume based on the isopachs and inversion agree on a total ejected tephra mass of value of 0.5 km^3. However, the volume may be larger (1.2 km^3) according with the inversion performed whith the metod of Sulpizio (2005). The value of column height obtained with the inversion and in agreement with the isopleths data is 32 km, lower than the value obtained by Araña-Salinas et al. (2010). This value is more consistent with a volume of 0.5–1.2 km^3. **Paper II** presents a comparison of the parameters obtained with different inversion methods.

Uncertainties related to the definition of ESPs were accounted using probability density functions (section 3.1.1). Table 4.3 contains the ranges of main input parameters for the eruptive scenario (column height, eruption duration and mean grain size of ejected material). Once ranges were defined for eruptive parameters, a Gaussian PDF is assumed within minimum and maximum values. Input parameters for the modeling were subsequently sampled using the stratified sampling technique, as described in **Paper I** and in section 3.1.1.

Probabilistic hazard maps were computed at different FLs and for the critical airborne concentration thresholds introduced in Europe after 2010. Figure 4.5 shows probabilistic hazard maps of ash concentration produced at FL050 for two concentration thresholds:

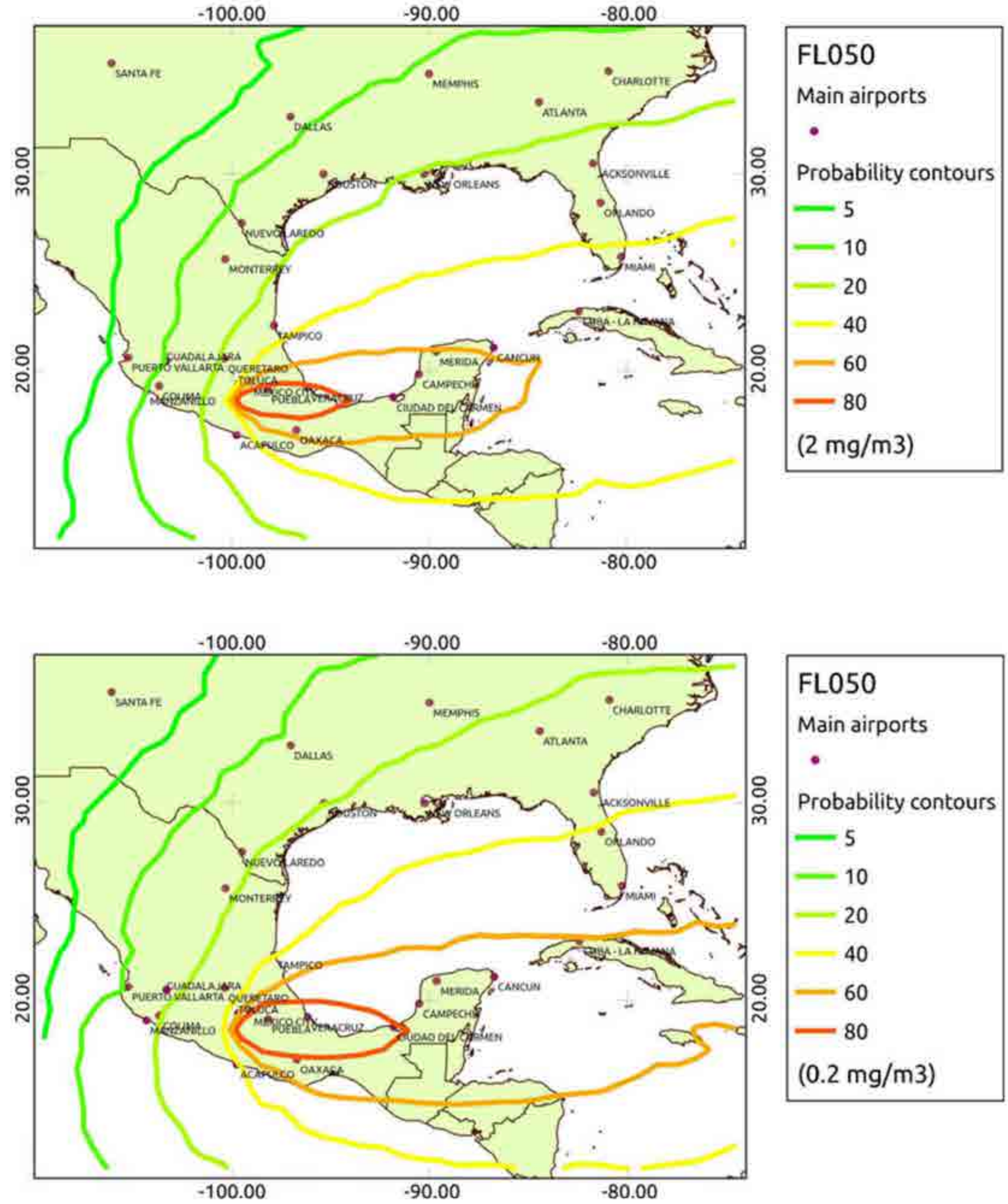

FIGURE 4.5: Probabilistic hazard maps of ash dispersal in case of occurrence of the selected eruptive scenario at Popocatépetl volcano. Contours give the probability to achieve values of 2 mg/m^3 (top) and 0.2 mg/m^3 (bottom).

2 mg/m^3 (top) and 0.2 mg/m^3 (bottom). Contours give probability, in percent, of exceeding the given threshold value.

The eruptive scenario simulated for Popocatépetl volcano is likely to affect the airspace of the Caribbean Gulf, reaching strategic airports such as Atlanta and Miami (U.S.) and La Habana (Cuba). The majority of the airports in North-central Mexico would have low to moderate probability of being affected by an ash concentration threshold of 0.2 mg/m^3, whereas the airports of Mexico City, Puebla, and Ciudad del Carmen would

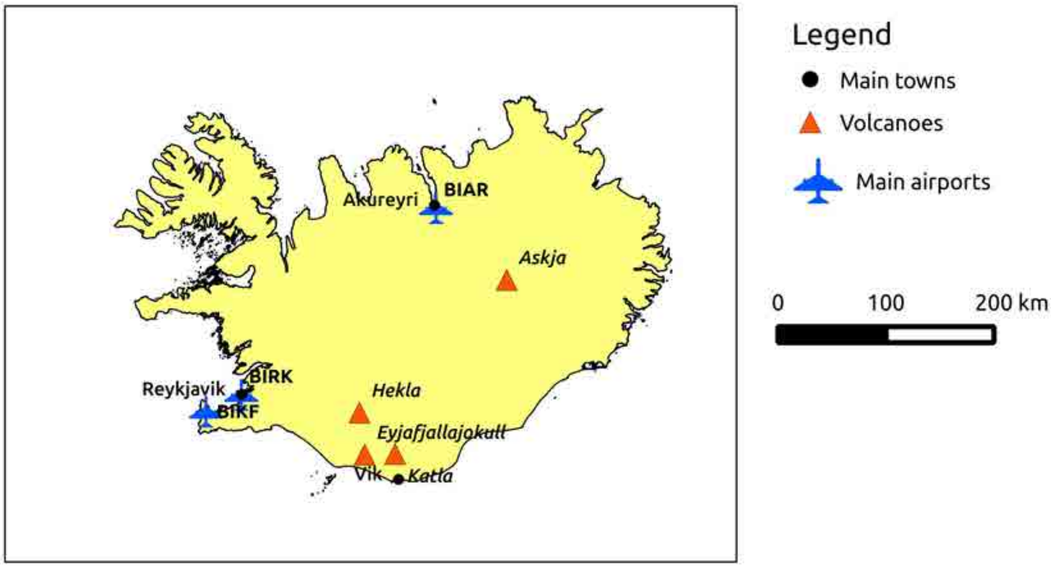

FIGURE 4.6: Location of the 4 considered active Volcanoes (Askja, Hekla, Katla, Eyjafjallajökull) and main Icelandic towns (and airports (identified by the ICAO code. BIKF = Keflavík, BIRK = Reykjavík, BIAR = Akureyri)

have more than 80% probability of exceeding this concentration threshold. An ash concentration value of 0.2 mg/m^3 could lead to re-routing and other operations to enhance air traffic security. For this reason, aerial corridors, especially those passing over south-central Mexico would have a high probability of being disrupted or even interrupted, with strong socio-economic consequences at National and Regional scale. The selected eruptive scenario would also affect several important US airports including Houston (Texas), Dallas (Texas), Miami (Florida) and Atlanta (Georgia, USA), the latest being the busiest airports of North-America, and particularly relevant for cargo operation. Detailed results are presented in **Paper II** and include the probability of being affected and the average persistence of critical ash concentrations for relevant airports.

Finally, given that the selected eruptive scenario can produce ash fallout at relevant distance from the volcano, a probabilistic hazard map was also produced for an ash load of 1 kg/m^2, which corresponds approximately to a deposit thickness of 0.1 cm. Results show that few millimeters ash fallout could affect many airports in the whole Mexican country, potentially interrupting crucial communication networks.

This study assessed the impact that a Plinian eruption similar to the Ochre Pumice eruption would have on the main airports of Mexico and adjacent areas. The hazard maps produced can support long-term planning that would help minimize the impacts of such an eruption on civil aviation and on the whole society.

4.1.4 Hazard assessment at 4 Icelandic volcanoes

This co-authored work (Biass et al., 2014, Appendix B) presents a multi-scale hazard assessment for tephra dispersal from 4 Icelandic volcanoes (Askja, Hekla, Katla, Eyjafjallajökull, Fig 4.6). These four volcanoes were selected for their high probabilities of eruption and/or their high potential impacts, and the associated hazard was assessed for dispersal at both national and European scale for different scenarios based on the eruptive record (documented by past geological studies). The modeling strategies adopted (Bonadonna et al., 2005; Biass and Bonadonna, 2012) are: Eruption Range Scenario (ERS), One-Eruption Scenario (OES), Long-Lasting Eruption Range Scenario (LLERS), Long-Lasting One-Eruption Scenario (LLOES). Ash dispersal was assessed for Hekla, Askja and Katla, while for Eyjafjallajökull only tephra accumulation was modeled (Biass et al., 2014, **Appedix B**). Scenarios are associated to a volcanic explosivity index (VEI) as described by Biass et al. (2014). Eruptive scenarios are summarized in Table 4.4 Each scenario was modeled assuming a statistical set of inputs using TEPHRA (Bonadonna et al., 2005) and FALL3D (Costa et al., 2006; Folch et al., 2009) models for tephra fallout and dispersal, respectively. The procedure for defining the range of ESPs and their probability distribution, as well as the modeling strategy adopted, is described in detail by Biass et al. (2014) (Appendix B).

Results of the hazard assessment at the national scale are probabilistic hazard maps for ground tephra accumulation. Given the rich historical record and high knowledge

Table 4.4: Eruptive scenarios considered in the tephra hazard assessment for 4 active Icelandic volcanoes: Hekla, Askja, Katla and Eyjafjallajökull. ERS: eruption range scenario; OES: one-eruption scenario; LLERS: long-lasting eruption range scenario; LLOES: long-lasting one-eruption scenario.

Volcano	Modeling strategy	Reference eruption	Column height	VEI	Eruption Duration
Eyjafjallajökull	LLOES	2010	2.5-7.8	2	40 days
Hekla	ERS	2000	6.0-16.0	2	0.5-1h
Hekla	ERS	1947	16.0-30.0	3	0.5-1h
Katla	LLERS	Historical moderate-large	10.0-25.0	-	1-4 days
Askja	OES	1875 (C+D phases)	22.8-26.0	5	1+1.5h (C+D phases)

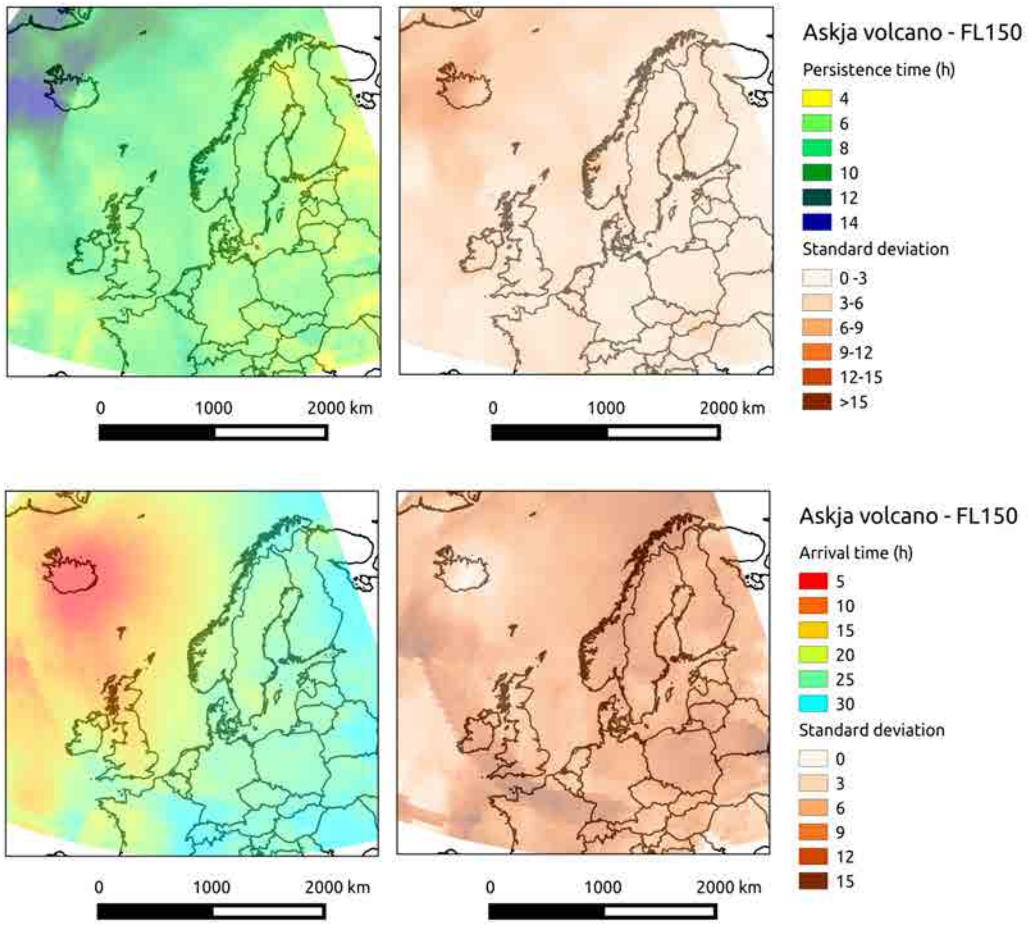

FIGURE 4.7: Example of average persistence (top) and arrival time (bottom) maps produced for Askja volcano. Maps of average time (left) are complemented with the respective standard deviation (right).

of Icelandic volcanic activity, it is possible for some volcanoes (e.g. Hekla) to associate scenarios with a "repose time", while other volcanoes have a short documented eruptive history or do not seem to follow evolution patterns.

Results of the probabilistic hazard assessment are tephra dispersal hazard maps for three ash concentration thresholds (corresponding to "zero tolerance" and to the concentration values introduced after the 2010 Eyjafjallajökull eruption). Similarly to **Paper I** and **II**, probabilistic hazard maps for ash concentration and maps of average persistence time were produced. This research also produced new maps of average arrival time, and complement persistence and arrival time with the calculation of standard deviation (Biass et al., 2014, Fig. 4.7). All maps are produced both at given FLs and accounting all FLs by performing a vertical integration.

Results of the hazard assessment show that:

- A 10-year recurrence rate eruption of Hekla (i.e., Hekla ERS 2000 type) only produces significant tephra accumulation close to the vent and in the southern part of Iceland. Ash concentration has a low probability (<1 %) of exceeding the threshold of 2 mg/m^3 at any flight level (FL) in the UK airspace.

- A 100-year recurrence rate eruption of Hekla (i.e., Hekla ERS 1947 type) produces substantial tephra accumulation in the southeastern part of Iceland. However, far-range ash concentrations still have low probabilities (<5 %) of affecting the UK airspace, with concentrations above the 2 mg/m^3 threshold at any FL.

- A moderate long-lasting basaltic eruption of Katla (i.e., Katla LLERS with tephra production over 1–4 days) is likely to produce substantial tephra deposition in southern Iceland. Ash dispersal has a substantial probability of reaching northern Europe, the UK (5–20 %) and central Europe ($\sim$ 5 %) with concentrations exceeding 2 mg/m^3 at any FL

- An eruption of Askja similar to that of 1875 (i.e., Askja OES 1875 type) is likely to produce massive tephra deposition in eastern Iceland. Ash dispersal has a substantial probability of reaching northern Europe, the UK (5–20 %) and central Europe ($\sim$ 5 %) with concentrations exceeding 2 mg/m^3 at any FL.

- For computational reasons, probabilistic approaches to assess the airborne concentration resulting from an eruption of Eyjafjallajökull similar to 2010 (i.e., Eyjafjallajökull LLOES 2010 type) were not applied.

Finally, in order to compare the relative impact of the different scenarios, one historical eruption was selected for each volcano for which ash dispersal and atmospheric concentrations were assessed using the same wind conditions of the Eyjafjallajökull 2010 eruption (14-24 April 2010). The selected eruptions include Hekla 1947, Katla 1918, Eyjafjallajökull 2010 and Askja 1875. The conclusion was that all eruptive events, if they were to occur, would likely disrupt the European air traffic, with the most important perturbations caused by eruptions like Katla 1918 and Hekla 1947.

4.2 Vulnerability assessment of air traffic system

4.2.1 Vulnerability and impact assessment at Nicaragua

During this research, a first-level exposure and vulnerability assessment was performed at local level for Ometepe Island and at National level for the Nicaraguan country. Results allow assessing expected impacts of the high-magnitude eruptive scenario previously defined for Concepción volcano (Section 4.1.1). This analysis was presented to the "GISRUK" conference (Liverpool) and the paper was published in the conference proceedings (Scaini and Folch, 2012). In addition, results were presented at the "Cities On Volcanoes" conference (Colima, Mexico, November 2013).

The first step of this analysis was the identification of exposed elements, i.e. the exposure analysis. Critical issues at local scale are the high vulnerability of buildings, the lack of redundancy of the road network (constituted by one main circumvention road and few unpaved secondary roads). The main exposed elements (strategic buildings such as schools and health care centers), activities (agriculture) and infrastructures (roads) of Ometepe Island are shown in Fig. 4.8. Buildings in Ometepe have a overall high vulnerability (**Paper I**), due to poor construction typologies and low maintenance of buildings. From the socio-economic point of view, agriculture has a strategic role. The main product is plantain, a variety of banana, and the production can be strongly impacted by ash fallout. Finally, tourism activities are increasing in the area, also thanks to the new airport of La Paloma, built in 2013.

From the local point of view, ash fallout in the island can produce direct and indirect impacts on exposed elements. Strategic buildings in Ometepe can be damaged by 100 kg/m^2 load at ground, while primary roads are likely to be affected by 1 kg/m^2 load. In particular, the primary road network, which measures about 50 km, has 70% probability of being totally impacted by ash fallout. Crops can be damaged by 1 kg/m^2 tephra load (total crops are $\sim$ 145 km^2 and have a 50% probability of being totally disrupted by the HMS scenario). Tephra accumulation at ground and in particular on the flanks of the volcano increases the probability of having lahars, triggered by rain. These phenomena may produce strong indirect impacts on population and exposed assets. Finally, tephra fallout and dispersal can cause the closure of La Paloma airport due to tephra accumulation and subsequent disruption of flights in the area. This can produce a strong impact on socio-economic activities including tourism.

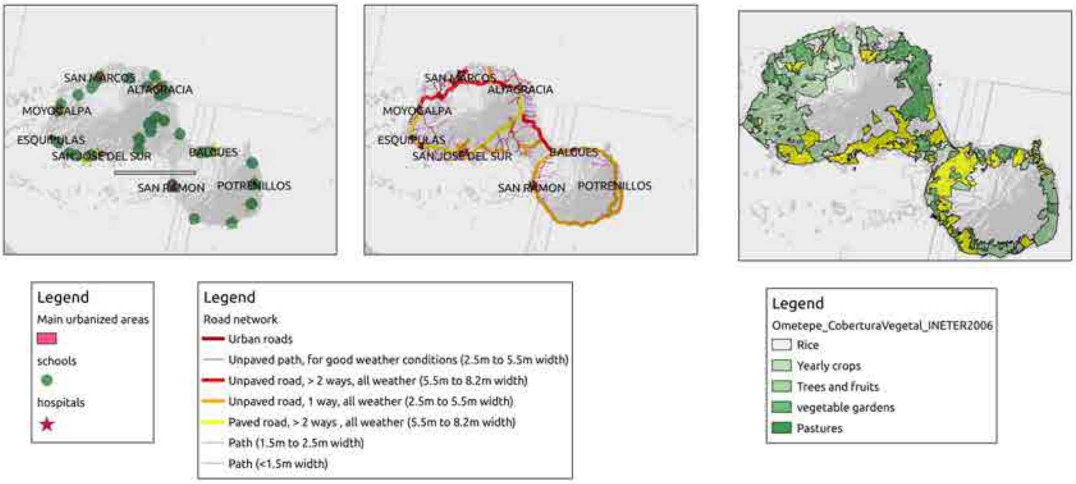

Figure 4.8: Exposed elements considered at local scale for Nicaragua: strategic buildings (left), road network (middle) and (agricultural activities)right.

From the National point of view, the agricultural activity represents the 19.6 % of GDP and employs a 30% of population. Agricultural production can be strongly affected by tephra fallout in the central part of the country. Major Nicaraguan agricultural exports to US are coffee, spices, beef, sugar, peanuts, hardwood, shrimp and lobster, while Nicaragua imports from U.S. mainly cereals and oil. The most important industrial centers are Managua, León, Chinandega and Granada (Fig. 4.9), and the main products are textile and leather products, processed food and beverage and chemical products.
Most of the goods produced in the central part of the country are likely to be exported by road and air traffic. Thus, transportation network has a high relevance for the national economy. Ash fallout from Concepción volcano can affect road traffic and disrupt road commerce. In particular, the main Nicaraguan trade vector is the Panamerican corridor. It is worth noticing that the presence of a railway would decrease systemic vulnerability by increasing redundancy of transportation system.
Finally, tephra produced by a high-magnitude scenario at Concepción volcano can affect substantially operations within the Nicaraguan airspace and main airports (Fig. 4.9). In particular, Managua airport is the main of the region, and has about 20 daily connections with U.S. (Miami, Houston, Atlanta) and main centro-american capitals (San Salvador, San José, Panamá). Given that U.S., Canada and El Salvador are Nicaraguan main partners in trade (60.2, 8.3 and 4.6% of GDP, respectively), a disruption of cargo operation main affect national economy. In addition, many touristic airports have been opened in the relevant touristic areas, including Ometepe. The disruptions of flights

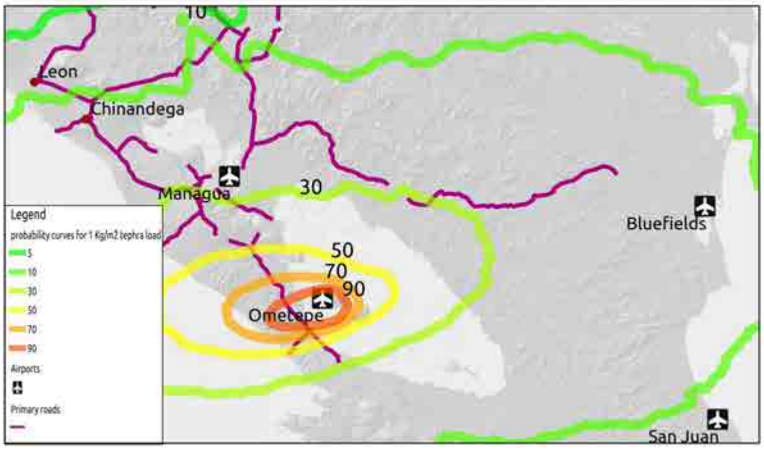

FIGURE 4.9: Impact of tephra fallout on main elements considered in the exposure analysis at National scale: airports and road network. Tephra fallout due to a high magnitude scenario can disrupt road traffic in the Pan-American road and air traffic at main airports (i.e. Managua) and smaller airports with imporance for tourism (e.g. Ometepe).

may thus cause relevant economic losses to the Nicaraguan economy.

Medium and high magnitude scenarios at Concepción volcano may cause partial disruption of Nicaraguan airspace due to ash-contamination, affecting local airports (e.g. Ometepe) and the main National airport of Managua, strategic for economic activities of the country. In addition, tephra fallout can affect local and regional economy by disrupting roads, and amongst them the Pan-american highway, causing an internal disconnection in the country (as mentioned in 4.1.1). Finally, tepha fallout may impact local population by damaging crops, highly relevant for both internal economy and exportation.

Socio-economic, transportation and import-export data for the analysis were gathered in the web pages of National and International institutions such as the Empresa Administradora de Aeropuertos Internacionales (EAAI, http://www.eaai.com.ni/), the Airport Council International (ACI, http://www.aci-na.org/), the Office of the United States Trade Representatives (http://www.ustr.gov/), the United States Department of Agriculture (USDA, http://www.usda.gov/wps/portal/usda/usdahome) and the Central Intelligence Agency (CIA) World Factbook (https://www.cia.gov/library/publications/the-world-factbook/).

4.2.2 Vulnerability and impact assessment or European air traffic network

This PhD research produced the first vulnerability and impact assessment methodology specifically defined for air traffic network. Due to the high impact of the 2010 Eyjafjallajökull eruption on air traffic network, this issue became particularly relevant at European scale. Systemic and socio-economic vulnerability of the European air traffic network to tephra dispersal was analyzed, estimating expected impacts in case of occurrence of the eruptive scenarios defined by Biass et al. (2014) for the considered Icelandic volcanoes (Askja, Hekla, Katla and Eyjafjallajökull, Fig. 4.6). The analysis has been performed at both national and European scale.

4.2.2.1 National scale

Given the strong impacts of tephra fallout at local scale, the vulnerability and impact assessment analysis has been also performed for tephra fallout (Biass et al., 2014, Appendix B). Hazardous scenarios considered for the Icelandic case-study, and in particular at Hekla, Askja and Katla, are likely to produce impacts on strategic infrastructures (i.e. electricity network and power plants). The exposed elements identified in the exposure analysis are: population, strategic buildings (hospitals, local health care centers and schools, which can be used as ash shelters), electricity network, hydroelectric and geothermal power plants, economic activities (production sites, main cities, agricultural areas) and presence of water supplies. The main exposed assets considered in the analysis are summarized in Fig. 4.10). The vulnerability analysis, developed from a systemic point of view, was applied only to the relevant indicators for the hazard at stake, and limited by the data availability. In particular, the vulnerability was analyzed for electric power plants and electricity network, road network and agricultural activities.

Eruptions at Hekla may be particularly problematic due to its proximity to most Icelandic power plants. Scenarios at Askja and Katla volcanoes can produce substantial impacts on agricultural activities (mainly pastures). Finally, road network can be disrupted by tephra fallout, in particular in the South-East of the country. Tephra fallout is not likely to impact main Icelandic airports (Keflavík, Reykjavík and Akureiri, Fig. 4.6) due to the dominating Eastwards winds. Results of the national-scale analysis are described in detail in **Paper III**.

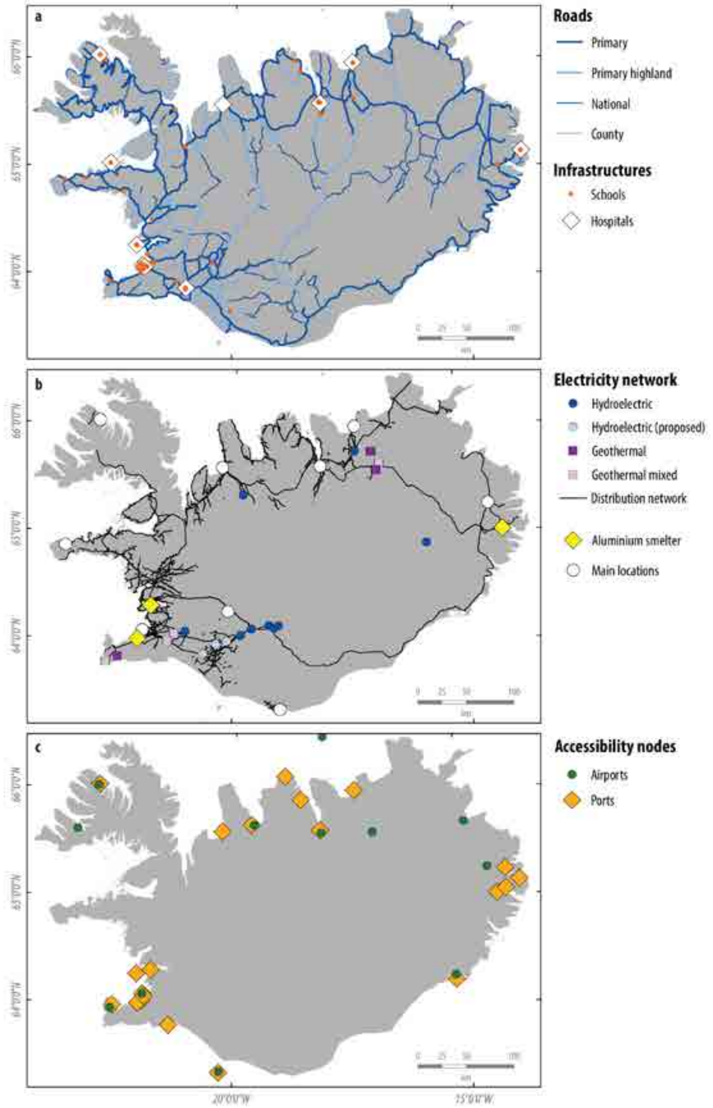

FIGURE 4.10: Exposure maps for (a) road network and critical infrastructures; (b) electricity distribution network, hydroelectric and geothermal power plants, production sites and main locations (urban areas); and (c) main transport nodes: ports and airport.

4.2.2.2 European scale

The analysis at the European scale is based on three exposed elements: airports, air traffic routes and Flight Information Regions (FIRs). Results of the vulnerability assessment at European scale (Fig. 4.11) allow identifying the strategical features (airports, routes) for the European air traffic network. The analysis is performed for the whole system and for specific subsystems (e.g. the air traffic between Iceland and U.K., Fig. 4.11, bottom).

In addition, the methodology allows assessing the relevance of air traffic for European regions, based on a combination of four regional indicators: population (Eurostat, 2013,

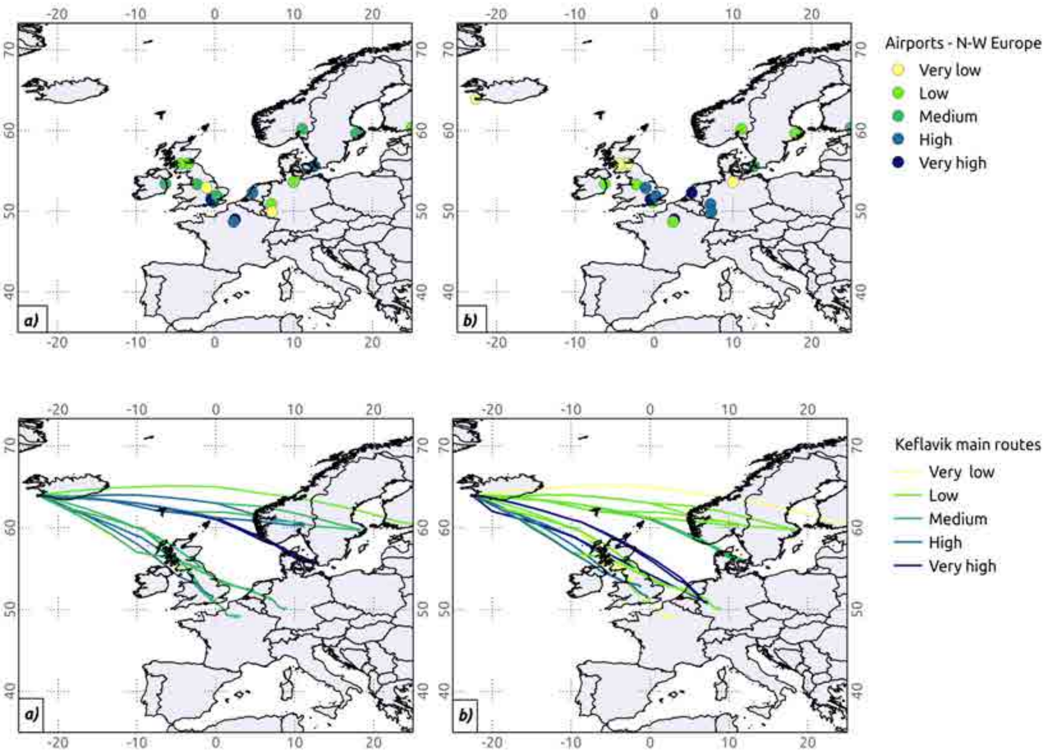

FIGURE 4.11: Results of vulnerability assessment for exposed elements: airports (top) and routes (bottom), for passengers (left) and freight (right) air traffic

data from 2012); total number of passengers and tonnes of freight transported by air (Eurostat, 2013, data from 2011); and multimodal accessibility, which takes into account the presence/absence of alternative transport modes and their cost (ESPON, 2004; TRACC, 2010, p. 17). This research proposed a first-level assessment of socioeconomic vulnerability by combining these four indicators under the assumption that vulnerability increases when the dependency on air traffic is higher and the multi-modal accessibility lower. All indicators refer to the 2003 NUTS-2 regions (Nomenclature of Territorial Units for Statistics), a hierarchical system for dividing the economic territory of the EU for the application of regional policies. The combination of demographic, trade and accessibility information identifies NUTS-2 regions with higher dependency on air traffic (Fig. 4.12), i.e., those more vulnerable to air traffic network disruptions. For example, Ireland has a high vulnerability because it is an island (which inherently has a low multi-modal accessibility) and has strong social and commercial relationships with the UK, resulting in high socioeconomic impacts in the event of air traffic disruption. Also, Nordic countries such as Denmark and Norway are likely to be affected, in particular those regions with lower multi-modal accessibility. Flexibility of the transportation system and

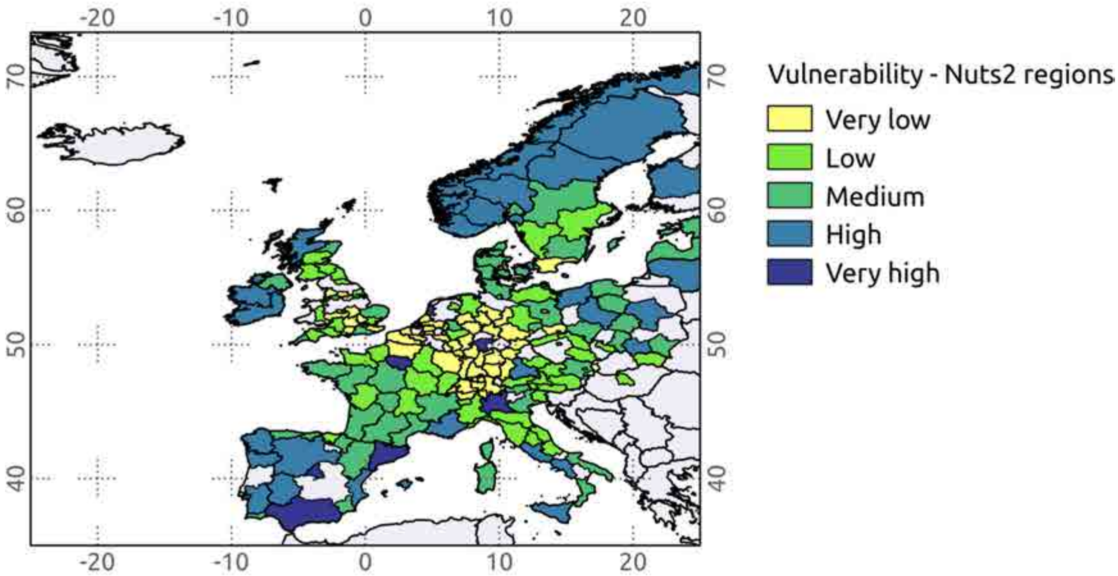

FIGURE 4.12: Results of vulnerability assessment for European NUTS-2 regions, obtained by combining demographic, trade and accessibility information. The map allows identifying NUTS-2 regions with higher dependency on air traffic and therefore more vulnerable to air traffic disruptions.

multi-modal accessibility are in fact critical factors that strongly influence the societal response to air traffic disruptions (Alexander, 2013). Moreover, a strategy that allows taking advantage of all different transportation means can strongly reduce losses during emergencies, as shown by Jones and Bolivar (2011) for the case study of Malta during the 2010 aviation disruption.

Finally, the methodology allows estimating expected impacts on FIRs, the spatial unit currently adopted for air traffic management in Europe. In fact, air traffic management is based on the capacity of airspace sectors, which include several FLs (Cook, 2007). For these reasons, and given that the FIRs unit is maintained in case of volcanic eruptions, expected impact maps at FIRs may be particularly useful for aviation stakeholders. The methodology produces comprehensive impact maps for FIRS that include the expected impacts at all FLs and provide a synthetic, conservative and meaningful results. Such maps can support for the development of an SRA and other risk management plans.

Results of impact assessment at European scale (Fig. 4.13) point out that the considered scenarios at Hekla volcano, characterized by lower magnitude and repose time, can affect Icelandic and U.K FIRs, and should therefore be taken into account due to their higher frequency of occurrence. The occurrence of higher-magnitude eruptions at Askja and Katla, having higher repose time, may cause substantial impacts to European air traffic, reaching strategic features in central Europe. Finally, all eruptions can cause

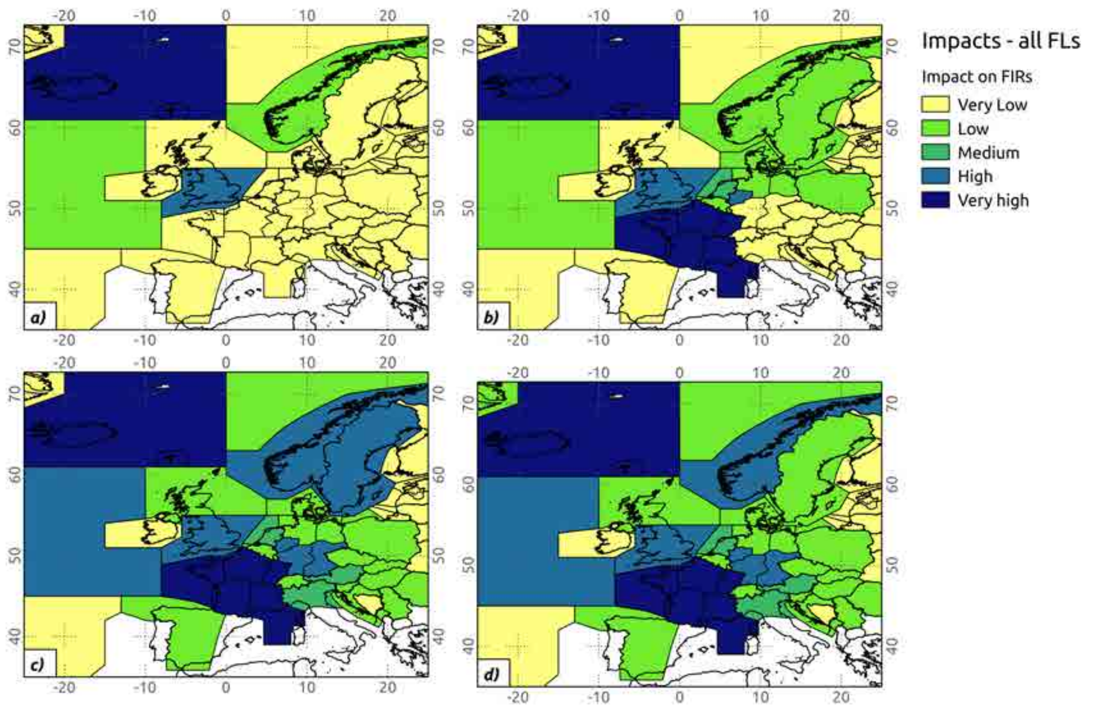

Figure 4.13: Expected impact at European FIRs in case of occurrence of the considered eruptive scenario at Hekla (a,b, respectively for 2000 and 1947-type scenarios), Askja (c) and Katla (d)

socio-economic impacts at local scale (i.e. disrupting important connections for local economies) and, for higher-magnitude and/or long-lasting eruptions, at regional scale.

Results at the European scale show that:

- The occurrence of a low-magnitude scenario at Hekla (see Biass et al., 2014 for details) is likely to have very high impacts on the Reykjavík FIR ($\sim$ 950 passengers stranded for at least 5 h) and high impacts for the London FIR ($\sim$ 23000 passengers stranded for at least 3 h).
- The occurrence of a higher magnitude scenario at Hekla is likely to have very high impacts on the Reykjavík FIR ($\sim$ 1500 passengers stranded for at least 8 h) and high impacts for the London FIR ($\sim$ 27000 passengers stranded for at least 4 h). The FIR of Paris, Brest and Marseille would also be strongly impacted.
- The occurrence of considered scenario at Askja is likely to have very high impacts on the Reykjavík FIR ($\sim$ 3600 passengers stranded for at least 18 h) and high impacts for the London FIR ($\sim$ 60000 passengers stranded for at least 8 h). FIRs above France, Germany and Scandinavia would also be impacted.

- The occurrence of the considered scenario at Katla is likely to have a very high impact on the Reykjavík FIR ($\sim$ 4300 passengers stranded for at least 21 h) and high impact for the London FIR ($\sim$ 78000 passengers stranded for at least 10 h). It is also likely that FIRs above France, Germany and Scandinavia would be strongly impacted.

Results of the application of the vulnerability assessment methodology can support decision making at both national and European scales. In particular, impact maps on FIRs could improve preparedness and help develop risk mitigation actions in Iceland and support longterm risk management plans of companies that operate in the European airspace (e.g., SRA).

4.3 Impact assessment of European air traffic network

This research proposes one of the first GIS-based tools for assessing expected impacts of volcanic eruptions on air traffic. The tool was applied to two case study: a posteriori analysis of the Eyjafjallajökull eruption and its impacts, and expected impacts from a "worst-case" eruption at Katla volcano, described respectively in Scaini et al. (2011) and **Paper IV**. In particular, the first case-study makes use of a prototype of the tool, subsequently improved for the second application. Detailed results of the application of the tool to the eruptions of Eyjafjallajökull and Katla are presented respectively in Scaini et al. (2011) and **Paper IV**.

4.3.1 *A posteriori* analysis of the Eyjafjallajökull eruption and its impacts

The fist application of the impact assessment was an analysis of the Eyjafjallajökull eruption in 2010 and its impacts on European aviation. The 2010 Eyjafjallajökull eruption has been modeled by different authors using different TTDMs. Amongst them, Folch et al. (2012) simulated 10 days of the eruption (from 14th to 24th April 2010) using the FALL3D model (Costa et al., 2006; Folch et al., 2009). Given that the volcanological inputs relied on hourly-averaged radar observations of plume height and characterization of the ejected material, and because a posteriori simulations use better-constrained

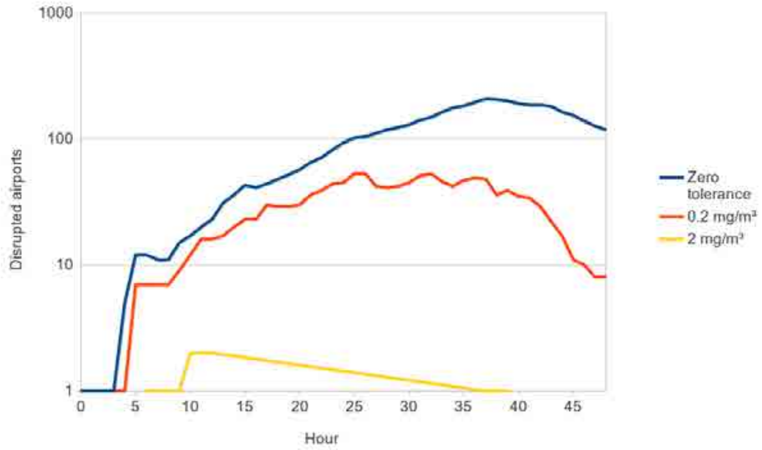

FIGURE 4.14: Hourly impacts on airports from 15th and 16th April 2010 at FL050. The plot shows the number of impacted airports for the critical ash concentration threshold considered (zero tolerance, 0.2 and 2 mg/m^3). The X-Axis origin corresponds to the eruption onset. Note that the Y-Axis has logarithmic scale.

(defined) meteorological and volcanological model inputs, it comes at no surprise that outcomes from reanalysis simulations can be different from those of forecasts.

This analysis was performed using the initial prototype of the GIS-based tool. At this stage, the elements considered for impact assessment were only airports and routes. The impact assessment procedure is similar to the one explained in section 3.2.3 for the final version of the tool, which includes also impacts on FIRs. Results of this analysis allow identifying hourly impacts (routes canceled and airports closed), stored into tables and maps in GIS and GoogleEarth formats. Temporal plots underline the peaks in the number of impacted airports and routes (Fig. 4.14 and 4.15). It is worth noting that, although based on real meteorological and air traffic data, the expected impacts from Eyjafjallajökull eruption are lower with respect to those documented during the event (Scaini et al., 2011). This is due to the high secondary impacts caused by air traffic disruptions (e.g. disruptions of flights due to airport/airspace closure or changes in crew/fleet allocation), not accounted by the tool. Also, the outcomes of the modeling performed by Folch et al. (2012) are different from the ones available to aviation authorities during the 2010 emergency.

Finally, this initial analysis points out that upper FLs (e.g. FL400) had a lower ash-contamination (due to the low eruptive column). It is therefore speculated that upper

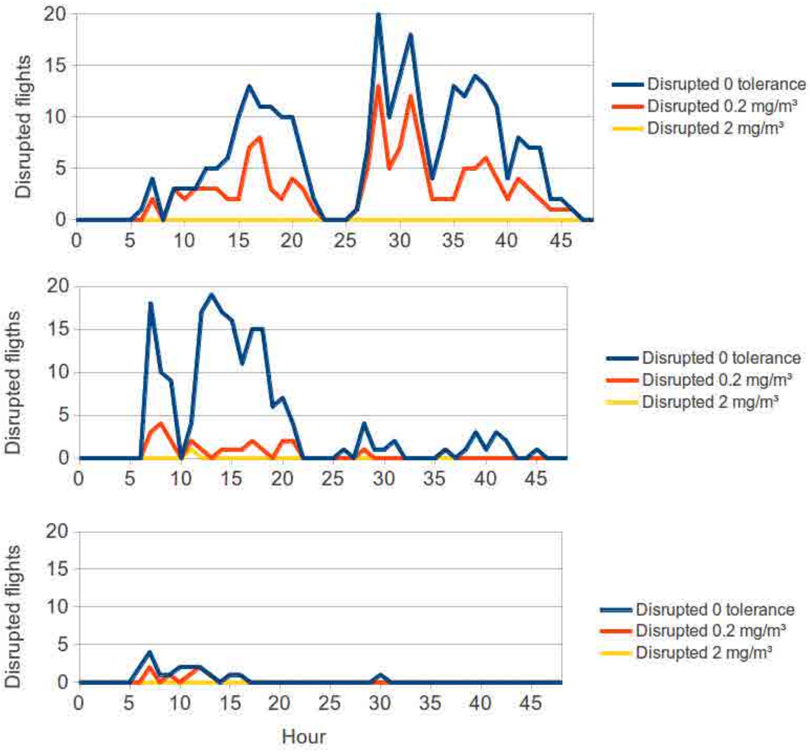

FIGURE 4.15: Hourly impacts for 15th and 16th April 2010 for FL 150, 200 and 250 (from top to bottom). The plot shows the number of impacted routes for the critical ash concentration threshold in case of zero tolerance (blue) and for the thresholds of 0.2 and 2 mg/m^3 (red and yellow, respectively)

FLs may host rerouted air traffic, in particular in case of low-column eruptions such as the Eyjafjallajökull event in 2010.

4.3.2 Impact assessment due to an eruptive scenario at Katla volcano associated to "worst-case" meteorological conditions

The final version of the tool has been applied to assess expected impacts from a "worst-case" eruption at Katla volcano, Iceland. The eruptive scenario is based on Biass et al. (2014) for Katla volcano. Explosive activity in Iceland is likely to impact the European air traffic network in case of winds blowing towards the main continent. Previous studies (e.g. Leadbetter and Hort, 2011; Biass et al., 2014) have estimated that the probability of having "unfavorable" wind conditions is of about 8-10% according to wind statistics for the 2000-2010 period, but this percentage increases during the winter season. In this particular example, a "worst-case" meteorological scenario is assumed, that is, a

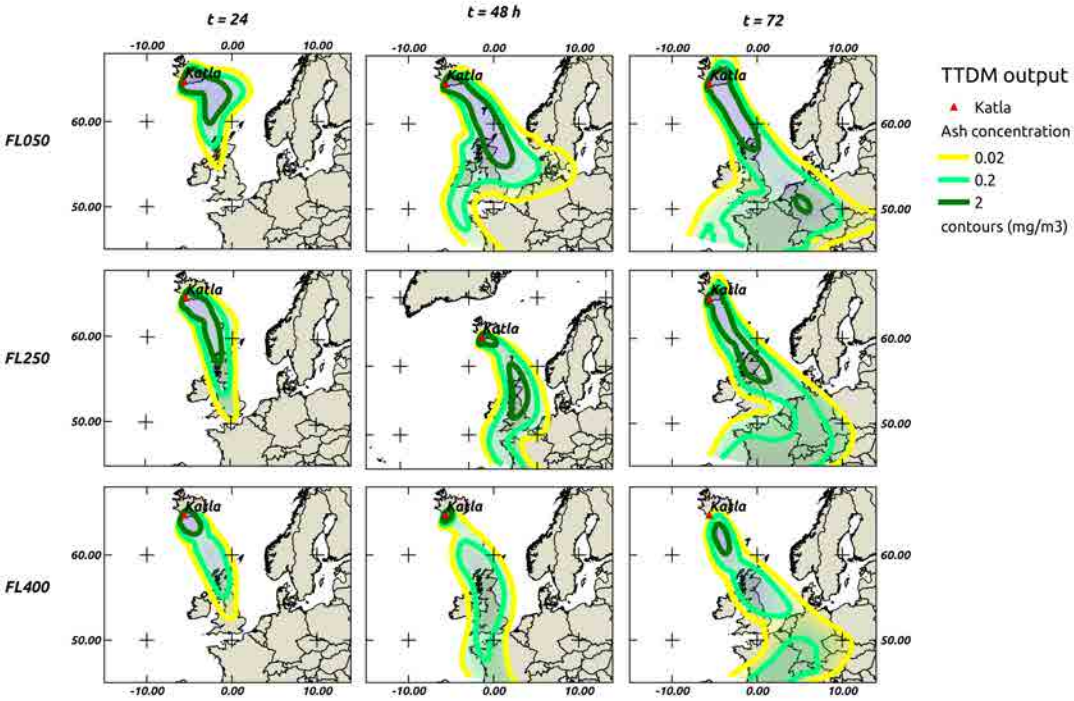

Figure 4.16: FALL3D model forecasts for the Katla eruptive scenario after 24, 48 and 72 hours from the eruption onset (left to right). Maps show contours of ash concentration equal to the three considered thresholds (0.002, 0.2 and 2 mg/m^3) at FL050, FL250 and FL400 (top to bottom).

synoptic weather situation is selected in which winds at altitude blow towards U.K and Central Europe. Ash dispersal in atmosphere was simulated using the FALL3D model (Costa et al., 2006; Folch et al., 2009), which furnishes hourly ash concentration values at each grid point and at equally spaced FLs (from FL050 to 400 at intervals of 5000 ft). The simulation starts on 1 January 2009 (coinciding with a "worst case" weather scenario) and lasts for 72 hours. Ash concentration values above 2 mg/m^3 are forecasted in U.K. and Germany at different times (Fig. 4.16). The impact assessment analysis lasts for 3 days, from the 1st to the 3rd of January 2009. Note that, in a real case, the analysis will be constrained by the length, time frequency and spatial resolution of the forecast(s) driving the impact analysis.

Figure 4.17 shows an example of impact maps produced for each time step of the analysis for the exposed features (airports, routes, FIRs). In addition, the tool produces plots that summarize expected impacts, that allow identifying the peaks of expected impacts. Fig. 4.18 show an excerpt of results, displaying total results of the impact assessment analysis for airports, routes and FIRs (from left to right). These results are

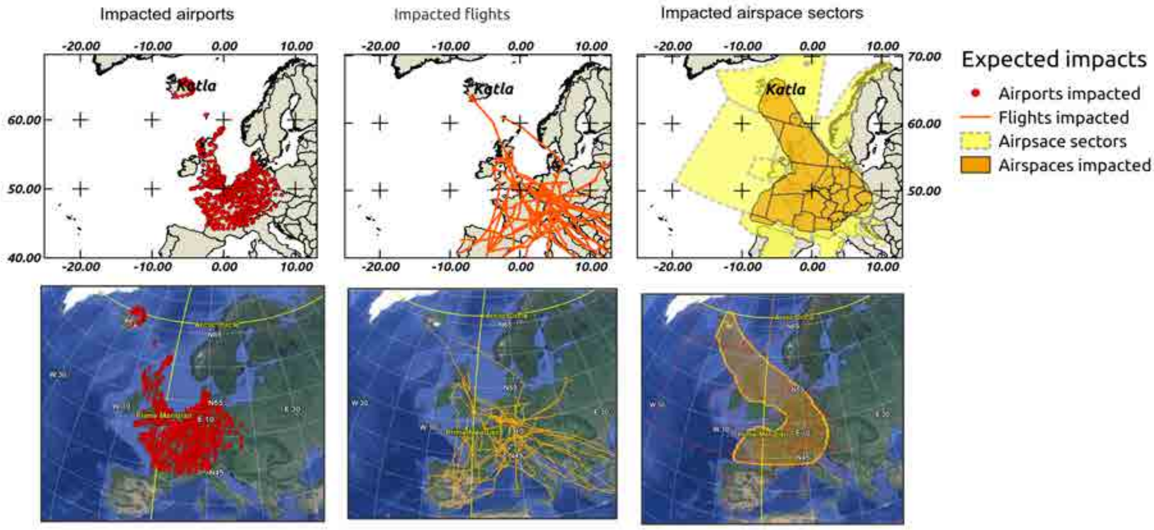

FIGURE 4.17: Impact maps in digital format (shapefiles, top, and kml, bottom) produced by the tool for the exposed elements (airports, routes, FIRs).

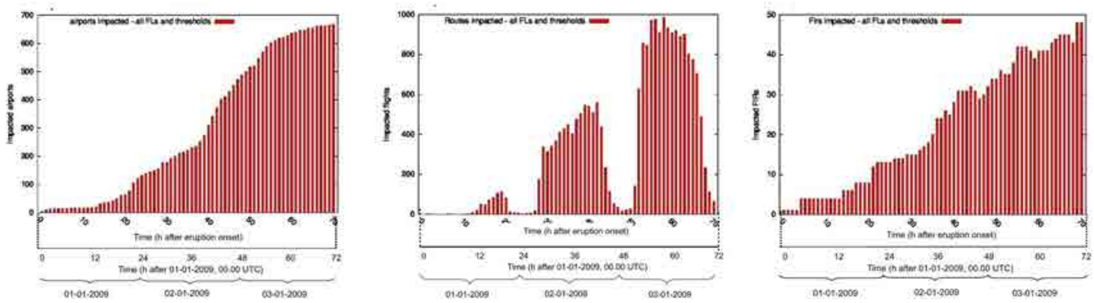

FIGURE 4.18: Impact assessment results: example of temporal series of the number of airport closed, routes canceled and FIRS impacted (left to right, respectively).

comprehensive of all FLs, while specific plots at given FL and for given concentration thresholds can be produced if needed. In the new prototype of the tool, the limitations of the tool presented in the previous section were partially tackled (see **Paper IV** for details). For instance, airspace contamination and flights disrupted due to airport closure were accounted. Results show that the contribution of airport closure to the total impacted flights is quite high, and underline the importance of establishing clear protocols for airport impact assessment (Fig. 4.19). In addition, based on the considerations presented in Scaini et al. (2011), the final version of the tool includes a simple model for re-routing of flights expected to be impacted. Results of the rerouting show that a low portion would be reroutable. Although this methodology has many limitations, this mitigation measure may be improved in future and would allow lowering economic impacts of disruption of a small fraction which could still be relevant in case of strategic

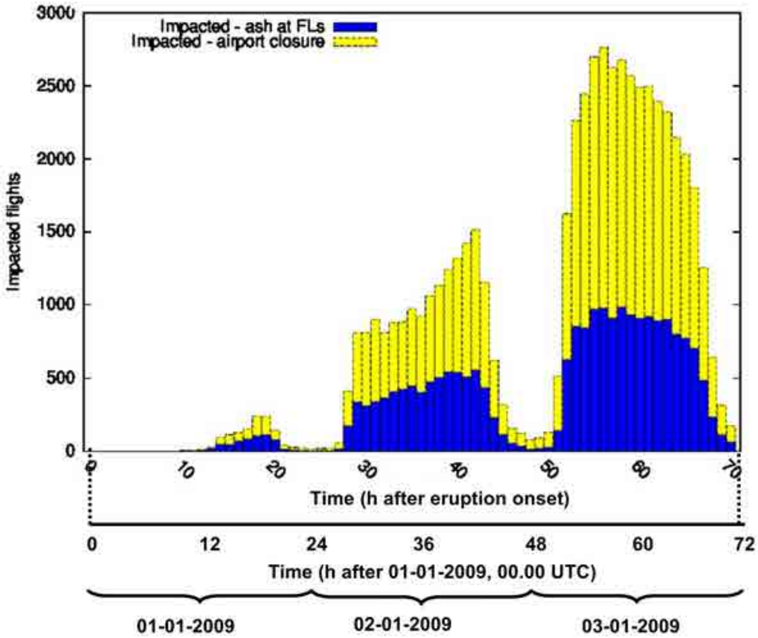

Figure 4.19: Contributions of forecasted in-flight encounters (blue) and airport disruptions (yellow) to the total number of impacted flights during the considered period

routes at regional/local level (**Paper III**).

Results of this analysis show that in case of "worst-case" meteorological conditions and high-magnitude explosive scenario, volcanic ash contamination may produce substantial impacts in most European airspace.

4.4 Aviation management during explosive volcanic eruptions: the stakeholders' perspective

A publication (Scaini et al., submitted) present the results of the first specific survey focused on different group of stakeholders involved in civil aviation management during explosive volcanic eruptions. Results give an overview of the stakeholders' opinion on main scientific developments and new procedures and point out the main open issues (e.g. definition of threshold for operating in ash-contaminated airspace, model uncertainties, operational constraints, knowledge gaps).

- **Survey respondents.** 5 sub-groups were identified amongst the respondents, which allow identifying the main opinions and needs of each group of stakeholders.

The stakeholders involved in civil aviation management during explosive volcanic eruptions can be divided into 3 main groups: scientific (S), aviation (A) and other (OT) stakeholders (i.e. representatives of activities indirectly related to aviation, such as import/export and insurances). In addition, the scientific group is constituted by atmospheric modelers (SM) and field and monitoring scientists (SF), while the aviation group (A) is constituted by aviation managers (AM) and employees (AE), including controllers, pilots and crew. A total of 115 responses were obtained, 66 of which complete (some non-mandatory questions could be skipped). Respondents are well distributed amongst the 5 groups.

- **Tephra Transport and Dispersal Models (TTDMs).** Participants belonging to the "atmospheric modelers" and "field and monitoring" scientific groups (SM and SF, respectively) that considered themselves familiar with TTDMs inputs (80% of the total) were also asked to associate the perceived level of uncertainty of each model input/output. Results are very homogeneous across these two groups, which in general have a similar background. However, a difference exists for uncertainties of monitored parameters such as plume vent exit velocity or ash cloud height and load, which are associated to a "high" uncertainty by the modeling community and to a "medium" uncertainty by monitoring community. Almost all respondents recognize the main input parameters used by most TTDM, i.e. wind field and the so-called Eruption Source Parameters (ESPs) such as eruption column height, particle size distribution (including fraction of fine ash), and mass eruption rate. However, specific answers underline that some respondents were not aware of the need of using air humidity for quantifying ash aggregation, as well as plume monitoring for source term assimilation.

  Not surprisingly, aviation stakeholders (A) use model outputs mainly for civil aviation management (36%) and airline management (26%), as illustrated in Figure 4.20. In contrast, the other groups (scientific and other stakeholders, S and OT respectively) use model results mostly for research purposes (37%). Approximately 20% of both groups use model outputs for emergency management. The most used model output format amongst all respondents consists of ash concentration maps in graphical format, used by over 50% of aviation stakeholders. This underlies the importance of providing ash concentration maps to the aviation stakeholders during a crisis, rather than or in addition to the "official" text messages (e.g. Volcanic Ash Advisories). Other data formats such as grib or NetCDF are scarcely used by aviation stakeholders (only 3% of group respondents). This is relevant because these data formats allow scientists to pack and include a large amount of information for further model post-process. In this sense, digital maps (i.e. files in GIS-compatible formats), used by 10% of aviation stakeholders, may act as an intermediate format for supporting decision-makers, providing these users with a more accessible but simultaneously detailed information on ash cloud properties.

After that, examples of several model graphical outputs were presented, including arrival and persistence time maps (Sulpizio et al., 2012; Biass et al., 2014) or probability maps resulting from ensemble model strategies (e.g. Folch, 2012). All respondents were very familiar with raster images, cloud extent maps and ash

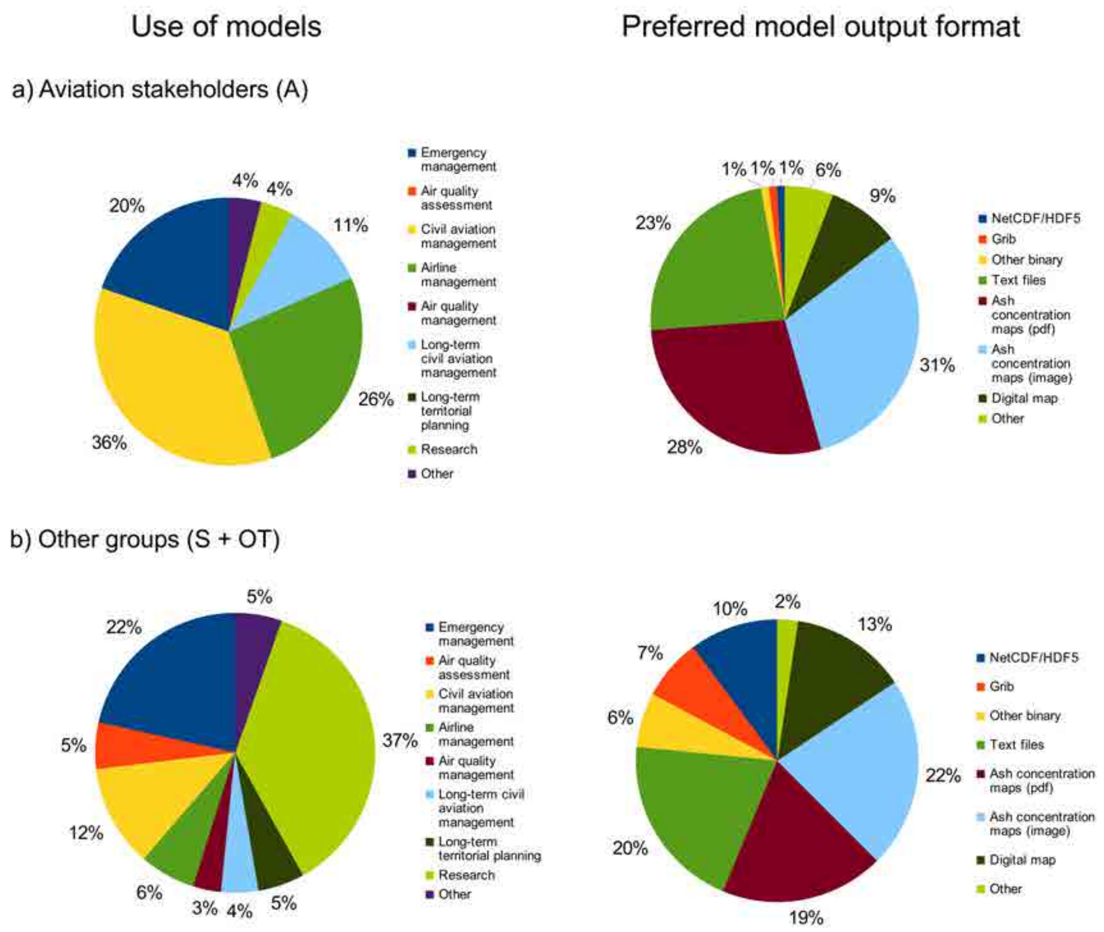

FIGURE 4.20: Use of tephra dispersal models amongst the survey participants and b) preferred output formats for the participants.

concentration charts (Fig. 4.21). With respect to usefulness, raster images and ash concentration charts are considered the most useful, followed by cloud extent maps. Finally, probabilistic curves are found useful by 75% of scientific stakeholders (S), but this percentage drops to 50% for aviation stakeholders (A).

Finally, survey participants were inquired about the introduction of standardized model outputs. 75% of respondents support the definition of standards for model outputs, and a larger percentage (90%) considers that standard outputs would enhance interoperability between different VAACs. The last point of this thematic section regards SO2 and its impacts on aircraft components (Casadevall, 1994; Osiensky and Hall, 2008). 65% of the participants consider SO_2 a medium-to-high hazard to civil aviation, while only 22% rank this hazard as low.

- **Criteria for defining critical thresholds.** This thematic section aims at surveying about different criteria to delimit fly/no fly regions in ash-contaminated airspaces and, in particular, on the use ash concentration thresholds considering the current level of uncertainties. Given that this aspect is particularly critical in Europe, the survey initially distinguished between global and European scales, but results did not show relevant differences. Figure 4.22 shows the results for the European scale, for the 3 main groups: aviation (A), scientific (S) and other stakeholders (OT) in order to determine if different perspectives exist regarding

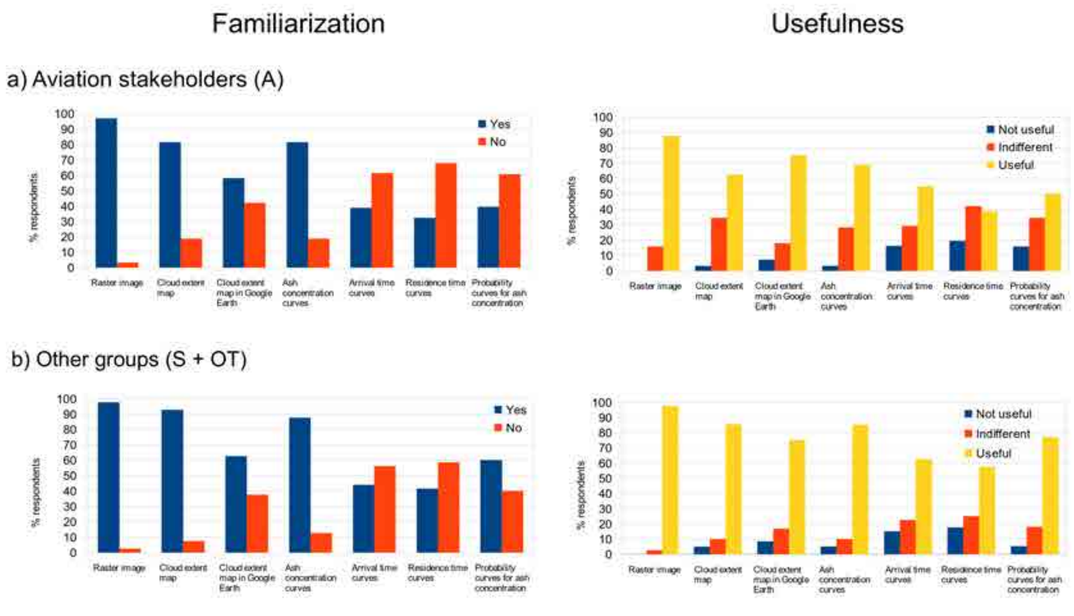

FIGURE 4.21: Familiarization and b) usefulness of modeling output formats according to aviation stakeholders (A) and other groups (scientific and other stakeholders).

the fly/no fly criteria. Results clearly show that the current "zero ash tolerance" criterion is the less popular and considered as less applicable by all groups. The criterion based on "visible ash" is particularly favored amongst aviation stakeholders, who consider it as "highly applicable" (>75%), but not amongst scientists (only a 22% favours this criterion). The criterion based on forecasted concentrations combined with a threshold value (e.g. the 2 mg/m^3 adopted in Europe during 2010), received an overall high consensus (> 60% of the three groups). However, this option is associated to a low applicability by aviation stakeholders. The most "popular" and "applicable" criterion results from a combination of different methods.

- **Forecast temporal resolution.** Traditionally, volcanic hazard assessment distinguishes between short and long term, where the former applies to emergencies and response (hours to days) and the latter to planning and preparation (years to decades). This distinction is not made by other stakeholders, for which "short-term" and "long-term" have different meanings. In order to clarify this point, participants were asked to indicate the temporal scales considered as short and long-term in their everyday work. Answers for all respondents and for the aviation

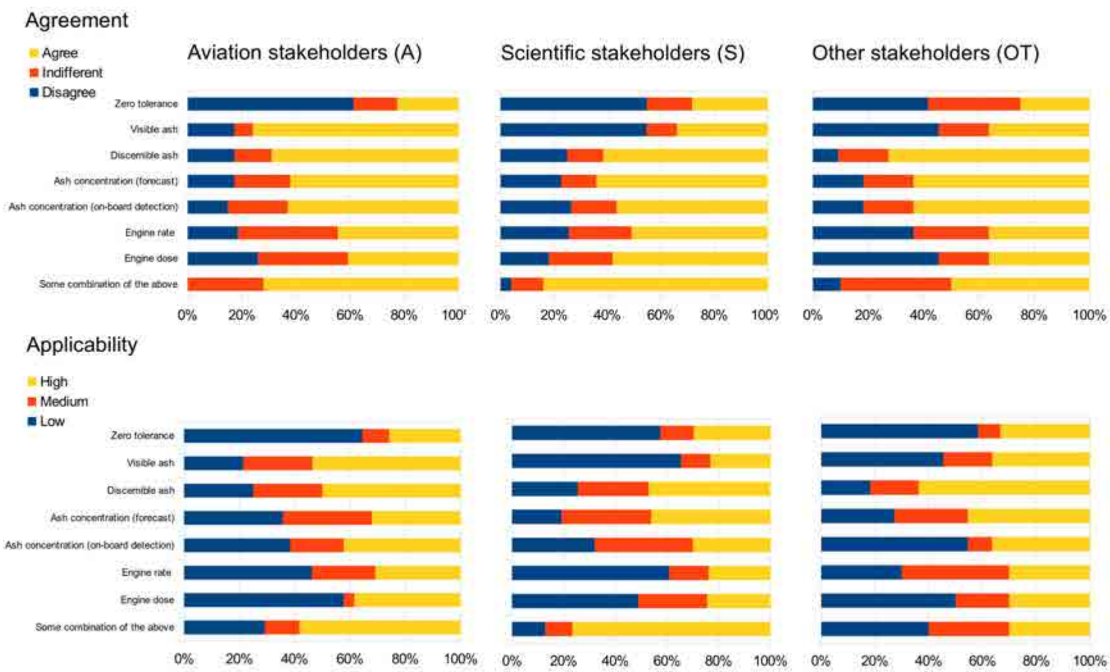

FIGURE 4.22: Agreement and b) applicability of the methods proposed for the definition of critical thresholds for aviation operations. Answers are showed for the three respondents groups: scientific (S), aviation (A) and other stakeholders (OT).

group show discrepancies between the aviation group and other respondents, in particular for long-term definition. Moreover, and given the importance of timely information exchange during an emergency, a question was posed on the preferred (and current) time frequency of forecasts and retrievals. All groups would like to receive forecasts every 1 to 6 hours and a substantial percentage (approximately 45%) of both aviation groups would prefer to receive updates at time intervals of less than 1 hour, much lower than the current ones (typically every 6 to 12 hours).

- **Air Traffic Management (ATM).** The two groups of participants related to aviation (about 30% of the total survey participants) were asked to rate the usefulness of having different types of data before and during an eruption. At any time, meteorological data was regarded as the most crucial one for most respondents. However, ash detection and quantitative data retrievals from satellites and on-board instrumentation were also considered as relevant. Ash dispersal maps (intended as model outputs in some map format) were ranked as useful by over 80% of respondents. In contrast, this community considers data on ash particle size/composition and ESPs (e.g. eruption column height) as less relevant for their decisions.

- **Use of GIS.** Given that some recent improvements (Scaini et al., 2011; **Paper III**; **Paper IV**) rely on Geographic Information Systems (GIS) for post-processing model outputs and further assessing expected impacts on aviation, stakeholders were asked about GIS-based software. A vast majority (85%) of the participants that are familiar with GIS-based software (Fig. 4.23). Most consider that GIS could support their current work and that raster data would improve their impact analyses (42 and 50% of the "modeling" and "monitoring and field scientists" sub-groups respectively). However, the percentage drops to <20-30% for aviation employees and managers. Finally, aviation managers and monitoring communities are quite familiar with Database Management Systems (DBMS) and spatial DBMS.

- **Current research on impact assessment.** Research is taking place to implement technical solutions to bridge the gap between communities. In particular, the tool presented in section 3.2 allows assessing expected impacts on aviation features (airports, routes, and airspace sectors) based on merging model forecasts with air

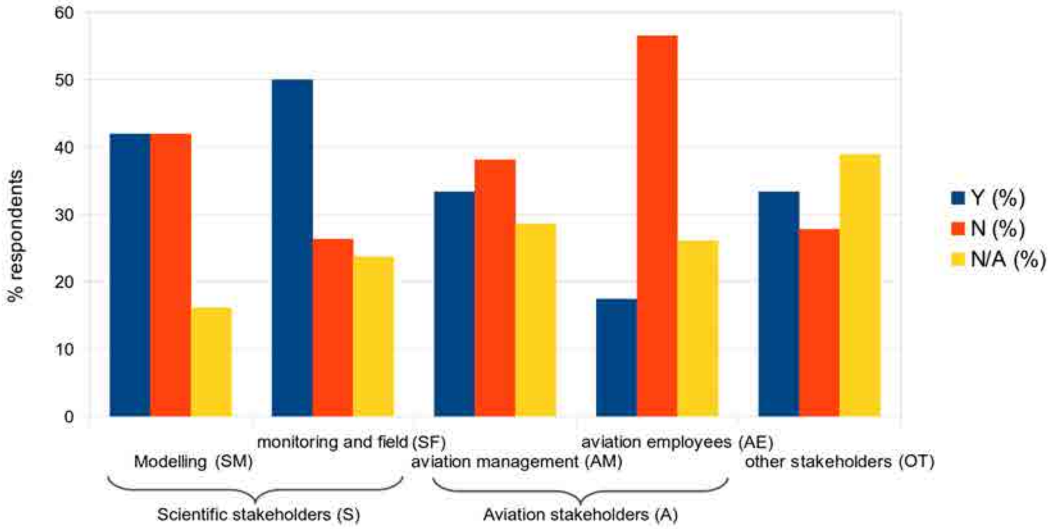

FIGURE 4.23: Familiarization of participant (divided into the 5 sub-groups defined in section 2.1) with Geographical Information Systems (GIS)

traffic data using a GIS-based environment. In order to better tailor this tool to end-user needs, the stakeholders' opinion was asked on different aspects.

First, aviation stakeholders (A) showed a high interest in impact assessment outcomes, rated as useful by more than 85% (the rest of stakeholders gave a high percentage of N/A to this question). Moreover, more than 80% considers that hourly updates of impacts would be useful in their work, confirming that managers would appreciate an increment in forecast frequency. Second, over 90% of aviation stakeholders rate as useful the automatic generation of impact maps, tables and series, particularly in formats compatible with visualization in Google Earth or GIS-based software. Impact results in the form of time series and hourly tables (e.g. list of expected impacted flights and airports) were rated as useful by 90 and 70% of aviation managers and employees and by more than 45% of aviation managers respectively. Third, given that results of impact assessments can also be classified in a qualitative way (i.e. "high", "medium", "low", etc.), the survey intends to identify which scales are more suitable to support decision-making. More than 70% of aviation stakeholders prefer a 3-class ranking. For quantitative assessment of impact on airplanes, a substantial fraction (39%) prefers the time flown in the ash cloud, followed by the flown distance. Finally, a majority would appreciate selecting input parameters for the impact assessment analysis. Higher preferences are obtained for geographical area and ash concentration thresholds, but aviation mangers and employees also showed interest on choosing specific FLs, airports and routes.

- **Recent developments.** This section surveys the opinion of stakeholders on different developments introduced after 2010. There is a general agreement on the importance of improving monitoring techniques, deploying on-board instrumentation and perform ad-hoc or opportunistic measurements from aircraft. However, aviation stakeholders give higher scores to specific aviation management practices such as SRA and training, while other groups (atmospheric modelers in particular) underline the importance of ensemble forecast and data assimilation techniques. Volcanologists are used to deal with a priori eruption scenarios that can provide a sort of "first-order" immediate forecast when an eruption starts. The aviation community shows a low awareness of this possibility but, nonetheless, aviation managers and employees consider that a priori forecasts could support air traffic management during unrest and increase preparedness. Most aviation managers and other stakeholders do not think that a priori forecasts can be confusing, but many aviation employees think so.

- **Probabilistic forecast framework.** Meteorologists and atmospheric dispersal models are familiar with probabilistic forecasts generated by means of ensemble techniques (i.e. an ensemble of runs with different models or different scenarios). In contrast, other communities are less used to deterministic prognostics and may be reticent to adopt a probabilistic framework (and a cost-benefit analysis) for decision-making. Results of the survey show that more than 65% of the respondents agree with the introduction of probabilistic framework in their work. However, 45% of respondents (mainly aviation managers and modelers) think that deterministic approach is easier to understand, which is a strong point of criticism against probabilistic strategies. On the other hand, given that probabilistic data are usually classified in a qualitative scale, respondents were asked which is the range of values commonly associated to "low" and "high" probabilities. Answers of each group range within two orders of magnitude for low probabilities and in one order of magnitude for high. This indicates that the eventual introduction of a probabilistic forecast framework may require of a specific communication strategy depending on the specific sector of application, in order to deal with the differences between groups of stakeholders.

- **Communication.** To conclude, the survey inquired if concepts commonly used in risk management can be a source of misunderstanding when used by multidisciplinary groups of stakeholders. The answers showed that this has been experienced by more than 85% of the participants. Amongst a list of terms commonly used in risk management, the concepts prone to confusion are “uncertainty”, “acceptable risk” and “confidence”, but most options are likely to generate misunderstanding between different communities and/or personal backgrounds. Almost 90% of the surveyed people considered that communication and information flow between different stakeholders during explosive volcanic eruptions should be improved.

This work presents the results of a survey performed by different groups of stakeholders involved in civil aviation management during ash-producing volcanic eruptions. Results give an overview of the stakeholders’ opinion on scientific developments, new procedures, and some open issues (e.g. definition of conditions for allowing aviation operations, model forecast uncertainties, scientific and technological gaps). In particular, the need for improving communication amongst different groups and creating a common knowledge is clearly revealed. Results of the survey serve also to enhance current research, providing useful insights for further developments and transfer into operations. End-user feedback has allowed compiling a list of requirements for future software tools to support aviation management and/or operations during explosive volcanic eruptions. Finally, these results highlight the factors that influenced recent developments and put the basis for the definition of future policies and procedures for managing air traffic during explosive eruptions.

4.5 Conclusion

This research produced probabilistic dispersal hazard maps for active volcanic areas, and maps of averaged arrival and persistence time and standard deviation (**Paper I, II**, Sulpizio et al., 2012; Biass et al., 2014). It also proposes the use and application of novel techniques (i.e. TMY, stratified sampling) to reduce computational cost of probabilistic hazard assessment based on numerical models (**Paper I**). In addition, the first methodology specifically focused on vulnerability assessment of air traffic to explosive volcanic eruptions was developed. The methodology was applied to the European air traffic network (**Paper III**). Results can support long-term risk management and design of mitigation measures. The impact assessment methodology was automated into a GIS-based tool (**Paper IV**), applied to two case-study for the European air traffic (Scaini et al., 2011 and **Paper IV**). Results allow identifying expected impacts and put the basis for the design of response strategies. Results of this research can support aviation management during explosive volcanic eruptions.

Chapter 5

Discussion and Conclusions

This research presents novel methodologies and instruments that can support and enhance civil aviation management during volcanic eruptions. Table 5.1 summarizes the main contributions of this PhD in the three main fields of research (hazard, vulnerability and impact) at both short and long-term. This chapter discusses the main limitations of this research, summarizes its main conclusions and points out the aspects that need to be improved.

Table 5.1: Main contributions of the PhD thesis

	SHORT-TERM	LONG-TERM
Hazard	Effective post-processing of TTDM outputs	New strategies for hazard assessment
Vulnerability/impact	GIS-based tool for impact assessment	Methodology for vulnerability and impact assessment

5.1 Discussion

5.1.1 Tephra Hazard modeling strategies

This research contributes to lower the computational cost of performing long-term probabilistic tephra dispersal hazard assessment using fully numerical TTDMs. The Typical Meteorological Year (TMY) allows reducing the computational cost of running mesoscalar meteorological models over a long time period (e.g. 10 years) by reducing the necessary number of simulations. This method is particularly suitable for local scale assessments, for which re-analysis datasets may have insufficient resolution. In future, this method may be improved, for example defining the TMY based on many wind samples at different areas. The TMY methodology is discussed in detail in **Paper I**.

The stratified sampling technique allows reducing the necessary number of simulations for the hazard assessment. However, the definition of Probability Density Functions (PDFs) for each parameter depends on the availability of data for the active volcano considered. This work performs tephra dispersal hazard assessment based on scenarios, defined using PDFs for ESPs. The issues related to the difficulty of choosing the ESPs, already recognized as a main issue for the volcanological community (Mastin et al., 2009; Bonadonna et al., 2011a; Bonadonna et al., 2013), are described in **Paper I, II** and Biass et al. (2014).

Finally, tephra dispersal hazard assessment results allow producing long-term maps focused on aviation needs (i.e maps of arrival and persistence time), that contribute to support volcanic risk management from the aviation point of view. Such maps allow transferring more information to the involved stakeholders and put the basis for the subsequent vulnerability and impact assessment. The potential use of these maps is presented and discussed in **Paper III**.

5.1.2 Vulnerability assessment of air traffic network

This PhD research presents the first vulnerability assessment of the air traffic network specific for volcanic ash. The main aim of the methodology is identifying which air traffic network features are expected to suffer impacts in case of explosive eruptions. The caveats of the vulnerability and impact assessment methodology are mostly discussed in **Paper III** and synthesized here:

- The methodology is quite general and, therefore, can be adapted to the specific characteristics of the area at stake. However, given the difficulty of gathering specific data, the methodology does not account for physical vulnerability of most features and for spatial inter- and intra-dependencies and cascading effects, which rely on the characterization of physical vulnerability, beyond the scope of this work.

- The systemic aspect is covered only in part, by identifying which specific elements and infrastructures are important to the system performance on a priori basis and assessing impacts upon them.

- This analysis requires a collaboration between involved stakeholders (infrastructure holders, service providers and end users) in order to characterize the interdependencies between elements that constitute the air traffic network. This analysis should start identifying where, how often, and for how long the air traffic will be interrupted. This analysis may be performed by splitting the network at specific delivery points, implying a detailed knowledge of its structure (Kjølle et al., 2012). In order to be realistic and produce usable results, this kind of analysis requires a collaboration between involved stakeholders (infrastructure holders, service providers, etc.). These aspects are relevant for the definition of management plans and response strategies of involved stakeholders.

- Eruptive scenarios used in **Paper III** are not associated with a probability of occurrence, due to the high uncertainties of such an approach (Biass et al., 2014). Thus, probabilistic hazard maps represent the expected situation conditioned to the occurrence of the scenario, i.e., the probability of having critical tephra concentration at a given point and FL, if the considered scenario occurs. A direct comparison between impact scenarios is thus possible only on a qualitative basis.

- The domain for the vulnerability analysis depends on the hazard assessment. The analysis performed for the European air traffic network (**Paper III**) identifies strategic airports both at European scale and for the North-Western European airspace. However, depending on the final aim of the vulnerability/impact assessment (e.g. analysis of a particular market segment), different study areas may be chosen. In addition, the principles of the vulnerability and impact assessment methodology could potentially be applied to geographic and socio-economic contexts different from Europe. Given that airspace classification varies substantially between geographic areas, the spatial unit for the socio-economic vulnerability analysis should be defined based on the administrative stucture of the studied area.

- The proposed methodology is focused on a specific hazard caused by explosive volcanic eruptions (i.e. volcanic ash fallout and dispersal). However, given that at both scales there are other hazards that potentially affect the exposed targets, outcomes of our vulnerability and impact assessment could support multi-risk initiatives and be interfaced with specific analyses. This work may therefore contribute to a multi-risk assessment including other hazards for aviation, such as extreme meteorological events, volcanogenic SO_2 or mineral dust.

This research also proposes a methodology to account, at fist-order, for indirect impacts produced by the disruption of a single feature (e.g. an airport or a connection) on National and Regional economies. The socio-economic vulnerability assessment methodology, although simplified, puts the basis for including socio-economic aspects in the process of volcanic risk management.
Tephra fallout produced by explosive volcanic eruptions can indirectly affect the air traffic system (e.g. disrupting airports). In addition, it can affect the socio-economic system (e.g. disrupting electricity network, road and rail transportation and productive activities). For these reasons, tephra fallout hazard assessment has also been performed at the active volcanoes considered (**Paper I, II, III**). Performing a multi-scale assessment, as done for the Nicaraguan case (4.2.1), allows grasping the local impacts of volcanic eruptions on National economies, often relevant to understand the socio-economic implications of air traffic disruptions and preventing strong economic losses.
In order to enhance the validity of the vulnerability assessment methodology, **Paper III** suggests a general framework for vulnerability data collection. Gathering such data would enhance vulnerability and impact assessment at active volcanic areas for both tephra fallout and dispersal.
The application of the vulnerability assessment methodology has given relevant results for the European area (**paper III**). London is recognized to be the core of the European aviation system, followed by Paris, Amsterdam and Frankfurt, according to the number of connections handled. The analysis has also identified the routes that have the highest socioeconomic relevance, and emphasizes the role of minor connections that, despite being secondary at the European level, are strategic for national economies. For example, the analysis of air traffic at London and Keflavík airports showed that London–Dublin and Reykjavík–Copenhagen are very important routes and their disruption could affect national economies and those of their commercial partners.

This analysis is also complemented by a first-level assessment of the socioeconomic vulnerability of Europe to air traffic disruptions. The combination of demographic, trade and accessibility information identifies European regions with higher dependency on air traffic, i.e., those more vulnerable to air traffic network disruptions. For example, Ireland has a high vulnerability because it is an island (which inherently has a low multi-modal accessibility) and has strong social and commercial relationships with the UK, resulting in high socioeconomic impacts in the event of air traffic disruption. Also, Nordic countries such as Denmark and Norway are likely to suffer systemic impacts due to air traffic disruptions, in particular at areas with lower multi-modal accessibility. Flexibility of the transportation system and multi-modal accessibility are therefore critical factors that strongly influence the societal response to air traffic disruptions (Alexander, 2013). Moreover, a strategy that allows taking advantage of all different transportation means can strongly reduce losses during emergencies, as shown by Jones and Bolivar (2011) for the case study of Malta during the 2010 aviation disruption.
Results of the impact assessment show that all eruptive scenarios for Icelandic volcanoes produce impacts in the London area, and that higher-magnitude scenarios can result in major impacts for the whole European air traffic system. Low-magnitude, short-duration activity does not result in high impacts on central European air traffic, but can disrupt relevant connections for the national economies involved (i.e., Reykjavík–Copenhagen, London–Dublin). Thus, results of this research show that long-lasting and/or weak eruptions can also produce substantial impacts to the air traffic system, and should therefore be taken into account in a comprehensive risk management assessment.

5.1.3 Expected impacts on aviation

This research defines an impact assessment methodology that can improve aviation management during explosive volcanic eruptions. Scaini et al. (2011) and **Paper IV** discuss the limitations of the methodology, underlining its assumptions:

- The impact assessment for airports assumes that airport operations are disrupted by the presence of ash at lower FLs. However, the regulation on airport operations in case of ash contaminated airspace does not provide specific information on this aspect. The definition of airport management strategies in case of volcanic ash contamination should be better defined, e.g. trough larger participation of airport managers and representatives in the VOLCEX exercises.

- The re-routing analysis assumes that all aircraft are able to reach FL400 without considering aircraft performance in presence of volcanic ash or constraints on airspace capacity. This is a strong simplification of real flight planning, that needs to comply with safety regulations.
- The methodology assumes that all airspace sectors extend from FL050 to 400. In practice, a differentiation exists between upper and lower sectors.
- The qualitative impact assessment classification of routes and airspace sectors should be defined in collaboration with the decision-makers using specific SRA.
- The eventual adoption of impact assessment criteria (both using ash concentration thresholds or engine ingestion) would ultimately require engine manufactures to specify engine tolerance.
- The extent of temporal and spatial buffers should be linked to forecast uncertainty using more objective quantitative criteria.
- At the moment, input parameters for the impact analysis are introduced through a simple configuration file. A graphical user interface (GUI) for the tool is still missing.

The impact assessment methodology proposed here improves risk management during explosive volcanic eruptions, accounting for current trends and developments of aviation regulation and is open to integrate new plans and strategies that may be developed in the future. In addition, it suggests possible mitigation measures (e.g. flights re-routing) in order to lower disruptions and subsequent economic losses.

An advantage of the tool is that it can potentially be interfaced with results coming from any ash dispersal model, and is therefore model-independent. In particular, the tool has a dedicated pre-processing routine to extract ash concentration maps from available TTDM outputs at a selected temporal resolution (depending on the temporal resolution of the modeling output). This allows performing the impact assessment at higher temporal resolution compared with the 6-hours maps issued by VAACs. The introduction of digital formats for ash dispersal forecasts (e.g. Google Earth, Webley et al., 2009), also envisaged by the International Airways Volcano Watch Operations Group (IAVWOPSG, 2014), may enhance the accessibility to ash dispersal forecasts and ease the use of tools like the one presented here. The tool pre-processing also accounts for uncertainties associated to the forecast, which may in future be characterized by new forecast strategies (for example, using data assimilation and ensemble forecast techniques). The tool may also be interfaced with many air traffic databases by loading data through the database template.

The tool allows estimating expected impacts on European air traffic network in case of eruption at Eyjafjallajökull and Katla volcanoes, respectively (Scaini et al., 2011; **Paper IV**). Results for the Eyjafjallajökull case-study can not directly be compared with the documented impacts because in 2010 the forecasts were different from the ones used in this study (based on more reliable modeling inputs). Moreover, it has been stated that many flight cancellations were not directly caused by the presence of ash, but were the consequence of the airspace closures (based on the forecasted ash presence). However, the comparison presented by Scaini et al. (2011) underlines the order of magnitude of differences between the 2010 impacts and the ones expected today. The aim of this comparison is not to criticize the air traffic management during 2010 but to underline the enormous opportunities for improvement in this field.

Paper IV shows that, for the Katla eruptive scenario under "unfavorable" meteorological conditions, impacts on the European air traffic are larger than those estimated by Scaini et al. (2011) for the 2010 Eyjafjallajökull event. Results confirm that explosive long-lasting eruptions from Icelandic volcanoes, even if of moderate intensity, can potentially disrupt strategic features (e.g. London and Amsterdam airports), causing substantial systemic impacts on the European air traffic system. This short-term analysis could be complemented with a long-term vulnerability and impact assessment, which should consider multiple runs under different eruption and meteorological conditions (Biass et al., 2014; **Paper IV**).

5.1.4 Communication between involved stakeholders

The improvement of communication between stakeholders was a complementary objective of this research. To this purpose, a survey comprehensive of stakeholders involved (directly and indirectly) in aviation management during volcanic eruptions was performed. This is the first survey that analyzes the differences between groups (modelers, field scientists, aviation managers and employees).

Results of the survey provide general insights and feedback on how to transfer on-going research into useful operational products. In fact, the answers indicated a demand to develop tools and procedures to support aviation management and/or operations in case of ash-contaminated airspace. All the stakeholders recognize the key role played by model forecasts. However, as already pointed out by the VAST project survey (Prata and Zehner, 2013), some factors limit the effective use of model forecasts and volcanic ash retrievals by end-users, e.g. the long delivery times, the time and space resolutions, or the lack of technological solutions to allow end-users to post-process the results. Results from the survey confirm the interest in increasing temporal resolution (frequency) of ash forecasts and impact assessments, in particular for aviation stakeholders. In addition, this community would welcome other types of products (e.g. maps of arrival and persistence time), to complement current ash concentration charts.

In addition, it is worth noticing that most respondents identified GIS and spatial DBMS as useful instruments to deal with spatially based hazards. However, a GUI is needed in order to facilitate the use of such tools. Finally, the survey underlined differences in the use of concepts like "low/high probability" or "long/short term", that have different meanings for each group of stakeholders. In particular, all the surveyed groups make use of probabilistic data during eruptions. The introduction of a probabilistic framework would help characterizing uncertainties of forecasts and subsequent impact assessments. However, the use of probabilistic analyses is more limited during everyday work. For this reason, common platforms for mutual knowledge transfer and cross-disciplinary training would be useful.

Results of the survey (Scaini et al., submitted) allow producing a list of requirements that should be considered in the design of new tools/instruments for aviation support during explosive eruptions (Table 5.2). It is worth noticing that the impact assessment methodology and the GIS-based tool presented in this PhD research are very flexible, and may include most of these aspects. For example, the tool could be completed with user-defined "rules" in order to be a real and proper DSS system. Future work should provide a more customizable tool (e.g. for critical concentration thresholds; ingestion or time/length indicators), in order to allow personalization of features based on user needs.

Results of the survey (Scaini et al., submitted) support the definition of response strategies and mitigation actions and the development of future research in this field.

TABLE 5.2: Critical issues pointed out by the survey (left) allow the definition of guidelines for tool development (right).

OPEN ISSUES	GUIDELINES
Use of TTDM for aviation purposes	Improve TTDM post-processing for aviation purposes
Use of GIS/DMBS	GIS/DMBS handling
Probabilistic framework	Include probabilistic analysis
Uncertainties	Account uncertainties
Customizable methodologies	Customizable options
Improve communication and cooperation	Integrated knowledge platform
User friendliness	GUI
Integration of timescales	Customizable timescales

5.2 Conclusions

The methodologies proposed in this research for hazard, vulnerability and impact assessment may be applied to many practical problems and are valid at different spatial and temporal scales.

Both long-term vulnerability and impact assessment and short-term impact assessment show that impacts of tephra dispersal and fallout are relevant for a comprehensive risk management at active volcanic areas. The vulnerability assessment methodology allows identifying the strategic features of the air traffic network (airports, routes), whose disruption may cause a higher systemic impact. Results of the impact assessment show that explosive eruptions can impact air traffic by disrupting relevant airports and their mutual connections (**Paper I, II, III, IV**), causing indirect socio-economic impacts. Results of the applications of these methodologies to the European air traffic network (**Paper III and IV**) show that main hubs (e.g. London, Paris) are strategic for the European air traffic activities. Both high-magnitude and low-magnitude long-lasting activity can produce substantial impacts on the air traffic network. Finally, peripheral areas of Europe (e.g. Nordic countries and islands), that rely on air traffic for import/-export and transportation, may be indirectly impacted by air traffic disruptions.

The application of these methodologies relies on data availability, as discussed in **Paper III** and **IV**. This limitation is valid for most existing vulnerability and impact assessment performed in active volcanic areas and, in general, to most natural hazards. **Paper III** provides a general framework for gathering and analyzing information related to exposure and vulnerability to tephra fallout, which puts the basis for the application of

this novel methodology to many other active volcanic areas.
In addition, the possible application of methodologies is influenced by an important factor: end-user needs, priorities and opinions. Results of the web-based survey (Scaini et al., submitted) contribute to the definition of end-user needs and allow establishing a list of requirements for the design of the new generation of tools to support aviation during explosive volcanic eruptions. In particular, results underline the need for improving communication amongst the different groups and creating a common knowledge, and suggest the creation of infrastructure for training and information sharing. This work strongly suggests that the further step in order to achieve an effective aviation management during explosive eruptions is to improve multi-disciplinary collaborations.

5.3 Future work

This PhD thesis contributes to bridging the gap between groups of stakeholders involved in air traffic management during volcanic eruptions. The research is focused on a rapidly changing topic, as showed by the large number of cutting-edge techniques and regulations introduced after 2010. Forthcoming changes may therefore influence the development of this research in new directions.
For these reasons, the methodologies presented here are defined for the "general purpose" of supporting air traffic management during eruptions, and provide flexible solutions that can be adapted to specific end-user needs. However, with the necessary modifications, this work may be integrated and applied to different purposes, supporting many stakeholders involved in civil aviation management.

Future developments of this research could allow creating a multidisciplinary group that may proceed in the research accounting for all the stakeholders needs. **Paper III** and **IV** and Scaini et al. (2011) suggest the main directions for future work:

- The vulnerability and impact assessment methodology should be improved in collaboration with stakeholders involved in air-traffic management and aviation operations. The analysis should be enhanced by specific quantitative analyses, accounting for spatial inter-dependencies and cascading effects. In addition, it should include a characterization of physical vulnerability of aircraft and the definition of reliable thresholds (still under discussion).

- The vulnerability and impact assessment should be complemented with a comprehensive socio-economic analysis. Such analysis may support the definition of mitigation measures and a reduction of future impacts of air traffic disruptions on society. For example, Jones and Bolivar (2011) describe the use of alternative transportation means as a temporary solution in case of air traffic disruptions. Knowing in advance the expected impacts on air traffic network would allow the definition of strategic plans.

- Both vulnerability and impact assessment methodologies could be applied to other case-studies (if the hypothesis of scale-free network are valid, or adapting it to different local/regional characteristics). These case-studies may include other hazards (for example SO_2 and mineral dust) and/or analyze their impacts on specific segments of the aviation market (e.g. low-cost or business aviation), according to their specific characteristics.

- The impact assessment methodology is now deterministic. In future, the tool could be interfaced with probabilistic ash dispersal forecasts (e.g. produced by an ensemble forecast).

- The GIS-based tool may complement existing tools such as EVITA, currently interfaced only with VAAC official forecasts but that could visualize TTDM outputs from other sources. In future, ash dispersal forecasts may be supplied by other providers, allowing end-users to download ash dispersal modeling outputs from repositories. It is worth noticing that a standard formats for TTDM outputs is envisaged by many stakeholders.

- The tool may be also integrated with a proper DSS engine, supporting the decision makers with a set of specifically defined rules. These rules should be defined based on SRA and other official regulations for flight operations in case of volcanic ash.

- The GIS-based tool has been designed as a Desktop-GIS type, but a migration to Server GIS is not excluded in the future. In order to increase its usability, the tool should also have a friendly and effective GUI. Finally, the tool architecture and design should be enhanced to fulfill operational requirements and integrated into a broader operational framework.

- The GIS-based tool may be enhanced in future by integrating new technologies (e.g. mobile and monitoring) and different timescales (long and short-term) into a comprehensive strategy.

Most of the future work will require a collaboration with other research groups with a strong background in other branches of science (e.g. social and economic sciences, operational research) and with aviation stakeholders (e.g aviation authorities, companies, etc.). The need for collaboration between different stakeholders and scientific groups is also underlined by the survey results and discussed in **Paper IV**.

In particular, the integration of different timescales (last point of the list) would support a comprehensive risk management focused on aviation during volcanic eruptions. Before and during unrest, the adoption of probabilistic framework would allow communicating uncertainties related to the definition of the expected eruptive scenario. Prior impact assessment analysis could be performed for a range of possible scenarios. The acceptable risk and the actions to take may be defined for each specific case.

Thus, future developments of long-term vulnerability and impact assessment methodologies will require the cooperation between scientific community, air traffic managers and other stakeholders (productive activities, governments, etc.).

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Appendix A

Full-tex publications included in the compendium

ATTENTION¡

Pages 144 to 171 of the thesis are available at the editor’s web

Paper I

Tephra hazard assessment at Concepción Volcano, Nicaragua

Scaini, C., Folch, A., Navarro, M.

Journal of Volcanology and Geothermal Research, vol. 219-220, pp. 41-51, 2012.
Doi:10.1016/j.jvolgeores.2012.01.007
http://www.sciencedirect.com/science/article/pii/S0377027312000145

Paper II

Long-range hazard assessment of volcanic ash dispersal for a Plinian eruptive scenario at Popocatépetl volcano (Mexico): implications for civil aviation safety.

R. Bonasia, C. Scaini, L. Capra, M. Nathenson, L. Araña Salinas, C. Siebe, A. Folch

Bulletin of Volcanology 76, 789, 2013.
Doi 10.1007/s00445-013-0789-z
http://link.springer.com/article/10.1007%2Fs00445-013-0789-z

Paper III

A multi-scale risk assessment for tephra fallout and airborne concentration from multiple Icelandic volcanoes - Part II: vulnerability and impact

C. Scaini, S. Biass, A. Galderisi, C. Bonadonna, A. Folch, K. Smith, and A. Höskuldsson

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Natural Hazards and Earth System Sciences
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A multi-scale risk assessment for tephra fallout and airborne concentration from multiple Icelandic volcanoes – Part 2: Vulnerability and impact

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Abstract. We perform a multi-scale impact assessment of tephra fallout and dispersal from explosive volcanic activity in Iceland. A companion paper (Biass et al., 2014; "A multi-scale risk assessment of tephra fallout and airborne concentration from multiple Icelandic volcanoes – Part I: hazard assessment") introduces a multi-scale probabilistic assessment of tephra hazard based on selected eruptive scenarios at four Icelandic volcanoes (Hekla, Askja, Eyjafjallajökull and Katla) and presents probabilistic hazard maps for tephra accumulation in Iceland and tephra dispersal across Europe. Here, we present the associated vulnerability and impact assessment that describes the importance of single features at national and European levels and considers several vulnerability indicators for tephra dispersal and deposition. At the national scale, we focus on physical, systemic and economic vulnerability of Iceland to tephra fallout, whereas at the European scale we focus on the systemic vulnerability of the air traffic system to tephra dispersal. This is the first vulnerability and impact assessment analysis of this type and, although it does not include all the aspects of physical and systemic vulnerability, it allows for identifying areas on which further specific analysis should be performed. Results include vulnerability maps for Iceland and European airspace and allow for the qualitative identification of the impacts at both scales in the case of an eruption occurring. Maps produced at the national scale show that tephra accumulation associated with all eruptive scenarios considered can disrupt the main electricity network, in particular in relation to an eruption of Askja. Results also show that several power plants would be affected if an eruption occurred at Hekla, Askja or Katla, causing a substantial systemic impact due to their importance for the Icelandic economy. Moreover, the Askja and Katla eruptive scenarios considered could have substantial impacts on agricultural activities (crops and pastures). At the European scale, eruptive scenarios at Askja and Katla are likely to affect European airspace, having substantial impacts, in particular, in the Keflavík and London flight information regions (FIRs), but also at FIRs above France, Germany and Scandinavia. Impacts would be particularly intense in the case of long-lasting activity at Katla. The occurrence of eruptive scenarios at Hekla is likely to produce high impacts at Keflavík FIR and London FIRs, and, in the case of higher magnitude, can also impact France's FIRs. Results could support land use and emergency planning at the national level and risk management strategies of the European air traffic system. Although we focus on Iceland, the proposed methodology could be applied to other active volcanic areas, enhancing the long-term tephra risk management. Moreover, the outcomes of this work pose the basis for quantitative analyses of expected impacts and their integration in a multi-risk framework.

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1 Introduction

Tephra dispersal and deposition during explosive volcanic eruptions can produce impacts at different scales, from local to continental. Compared to other volcanic hazards, tephra fallout is unlikely to cause casualties, but, nonetheless, it often produces high systemic and socioeconomic impacts (e.g., Wardman et al., 2012; Biass et al., 2012). Moreover, the presence of volcanic ash in the atmosphere disrupts aerial navigation and may produce additional socioeconomic impacts at larger scales, from regional to continental, depending on the eruption intensity and duration, ash properties and atmospheric circulation. For these reasons a comprehensive risk assessment of active explosive volcanoes that are located in areas with high population and flight density should always include the hazard associated with both tephra dispersal and accumulation. Iceland is amongst the most active volcanic areas in the world, hosting more than 30 volcanic systems that display different eruptive styles and a wide range of volcanic products (Thordarson and Larsen, 2006). In a companion paper, Biass et al. (2014) present a probabilistic tephra hazard assessment from four Icelandic volcanoes (Hekla, Askja, Katla and Eyjafjallajökull) selected for showing recent activity, different levels of historical record, and a variety of eruptive styles and activities. In this manuscript we present the associated vulnerability and impact assessment in order to support more effective mitigation strategies in Iceland and Europe. As for other natural risks, volcanic risk evaluation builds upon three factors: hazard, exposure and vulnerability (e.g., De la Cruz Reyna and Tilling, 2008). Exposure is a key element in risk assessment, since it "encompasses all elements, processes, and subjects that might be affected by a hazardous event. Consequently, exposure is the presence of social, economic, environmental or cultural assets in areas that may be impacted by a hazard" (Birkmann, 2013, p. 305). Thus, the identification of exposed targets largely depends on their location with respect to the impacted area for the considered hazard and to the type of hazard at stake. Finally, the exposure, although crucial for an effective risk assessment, does not account for the variability of response of people, infrastructure, goods or ecosystems to the hazardous event: such response depends on their susceptibility to be harmed or, in other words, on their vulnerability. Vulnerability can be defined as the potential of exposed targets to be directly or indirectly damaged by a given hazard. Definitions, conceptual frameworks and methodologies for analyzing and assessing vulnerability are very heterogeneous, although "there is a clear recognition of the importance of place-based studies in examining vulnerability" (Cutter, 2013, p. 1089). In the last decade, vulnerability has been largely recognized as a multidimensional concept, comprising different aspects (physical, systemic, social, economic, environmental, institutional, etc.) constantly interacting in time and space (Birkmann, 2006; Galderisi et al., 2008; UNISDR, 2009; Menoni et al., 2011). In particular, the concept of systemic vulnerability is becoming more widespread in the scientific literature and refers to the fragilities arising as a consequence of interdependencies among elements and systems within a given territory, which can reduce its overall functioning in the face of a hazardous event (Rashed and Weeks, 2003; Menoni, 2005; Galderisi et al., 2008; Pascale et al., 2010; Ensure, 2011). Territorial systems are characterized by a dense network of physical and functional interdependencies (Paton and Johnston, 2006; Hellstrom, 2007), and the potential impact of a hazard on a given element may reverberate on to others that are physically or functionally connected to the former. The concept of systemic vulnerability has been applied in several areas of natural hazards such as floods, earthquakes, tsunamis, etc. (e.g., Minciardi et al., 2005; Pascale et al., 2010), but in volcanology this concept has been introduced only recently (e.g., Galderisi et al., 2013). Systemic vulnerability has a particular relevance in the case of tephra fallout, which may produce much higher secondary than primary impacts; that is, the physical failure of an element may also impact other connected activities and infrastructures (Biass et al., 2012). For example, the failure of the electrical network can cause cascading effects on several productive activities, such as manufacturing, power generation, agriculture or tourism. Furthermore, tephra dispersal and deposition largely affect transportation networks, which are crucial for accessibility to urban areas and emergency facilities. Finally, social and economic aspects of vulnerability have been deepened in scientific literature since the 1990s, but an unequivocal definition of both social and economic vulnerabilities and of their mutual relationships is still missing (Parker and Tapsell, 2009; Tapsell et al., 2010). The aim of this analysis is performing a vulnerability and impact assessment analysis at national and European levels. Due to the large scale of the analysis and the lack of specific data, physical vulnerability is not considered in our assessment, with the exception of few specific elements of particular relevance (i.e., electric power plants and distribution network). A comprehensive assessment of physical vulnerability is beyond the scope of this paper. Moreover, we consider only one aspect of the systemic vulnerability, i.e., the a priori identification of elements and systems that are particularly relevant from a systemic point of view. We do not account for the cascading effects and spatial interdependences that may take place during the emergency. Through this simplified approach, the vulnerability and impact assessment presented here aims at identifying the areas that are likely to suffer the higher impacts, where more specific research should be performed. This approach is commonly adopted in risk management for hazardous phenomena whose physical impact on elements are not yet quantified, and in particular for those which do not cause large losses of life and socioeconomic impacts (Douglas, 2007). Iceland is considered a well-prepared and highly resilient country, but the traditional risk management strategies of the Icelandic Civil Protection have traditionally focused on the short-term reaction rather than on long-term land use planning (Jóhannesdóttir and Gísladóttir, 2010). As a consequence, there is a lack of specific studies on vulnerability of the Icelandic territory to tephra deposition, even though tephra fallout is a relatively frequent phenomenon in Iceland. Here we perform a vulnerability assessment taking into account that, according to the analysis of past events (Biass et al., 2014), agriculture, transportation and energy sectors are the most vulnerable to tephra accumulation. We focus on systemic and economic dimensions of vulnerability. To this aim, we define exposed targets, estimate vulnerability for each considered target, and evaluate the expected impacts for all the eruptive scenarios defined in the previous hazard assessment. Physical vulnerability of buildings is not considered because, according to the hazard analysis of Biass et al. (2014), expected tephra accumulations are unlikely to cause significant damage to buildings for the volcanoes and activity scenarios considered (proximal areas around the selected volcanoes are mostly uninhabited). Moreover, our analysis is performed at a national scale (the whole island), while physical vulnerability assessments require detailed on-site surveys, for example on building stock, which are usually performed at the local scale. However, we consider physical vulnerability of the electricity network because its failure can trigger relevant impacts on the whole of society. We also focus on the potential for temporary or permanent loss of economic activities, which is relevant to the maintenance of the level of welfare of the population. The disruption of flights caused by the 2010 Eyjafjallajökull event was economically significant for both Europe and Iceland (Sammonds et al., 2010; Oxford Economics, 2010; Alexander, 2013). Using the last 10 years of the ERA-Interim reanalysis data set, Biass et al. (2014) conclude that the probability of having upper-troposphere winds blowing towards central and northern Europe is 6–8 %, a value consistent with the 6 % found by Sammonds et al. (2010). Given the experience from 2010, these probabilities suggest that assessing the vulnerability of the European air traffic system to Icelandic ash dispersal is relevant for the management of volcanic risk in civil aviation, particularly since no vulnerability assessment of any air traffic system specifically focused on volcanic ash hazard exists. Wegner and Marsh (2007) and Wilkinson et al. (2001) underlined some relevant aspects of the European air traffic network and showed that it is a scale-free network highly vulnerable to the disruption of the main hubs. Based on this finding, we develop the first assessment of vulnerability of the European airspace to tephra dispersal. The analysis is based on the systemic approach and aims to identify the critical features for the system, i.e., the elements that can produce the highest systemic impacts on the whole European air traffic system in the case of failure. As we did at the national scale, we identify the distribution and the features of the exposed targets and define vulnerability indicators in order to evaluate the expected impact for the different eruptive scenarios considered in the hazard assessment.

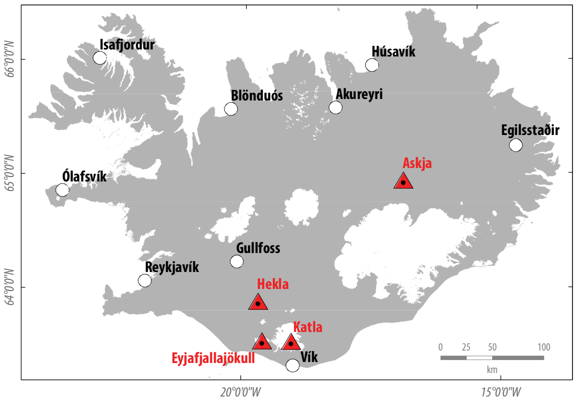

Figure 1. Map of Iceland showing the location of the four volcanoes considered in the hazard assessment and the main cities and towns. The administrative units (municipalities) used for the national vulnerability analysis are given in the Supplement.

This manuscript is arranged as follows. Section 2 overviews the eruptive scenarios for the selected volcanoes and the findings from the hazard assessment of Biass et al. (2014). Section 3 presents the vulnerability and impact assessment of tephra fallout at the national scale, and Sect. 4 presents the vulnerability and impact assessment of tephra dispersal at the European scale. Section 5 discusses the advantages and disadvantages of the proposed methodology and the future research developments required to improve it. Finally, Sect. 6 concludes the paper with a summary.

2 Eruptive scenarios and results from the hazard assessment

A companion paper (Biass et al., 2014) presents a multi-scale probabilistic tephra hazard assessment for different eruptive scenarios of four highly active Icelandic volcanoes (Hekla, Askja, Katla and Eyjafjallajökull; Fig. 1). These four volcanoes were selected for their high probabilities of eruption and/or their high potential impacts, and the associated hazard was assessed for dispersal at both national and European scale for different scenarios based on the eruptive record (Table 1). Scenarios are associated with a volcanic explosivity index (VEI) as described by Biass et al. (2014). Each scenario was modeled assuming a statistical set of inputs using TEPHRA (Bonadonna et al., 2005) and FALL3D (Costa et al., 2006; Folch et al., 2009) models for tephra fallout and dispersal, respectively. Results of the hazard assessment at the national scale are probabilistic hazard maps for ground tephra accumulation. Given the rich historical record and high knowledge of Icelandic volcanic activity, it is possible with some volcanoes (e.g., Hekla) to associate scenarios with a "repose time", while other volcanoes have a short documented eruptive history or do not seem to follow evolution

Table 1. Synthesis of the eruptive scenarios considered in the tephra hazard assessment (Biass et al., 2014). ERS: eruption range scenario; OES: one-eruption scenario; LLERS: long-lasting eruption range scenario; LLOES: long-lasting one-eruption scenario. Tephra accumulation and dispersal was assessed for Hekla, Askja and Katla, while for Eyjafjallajökull only tephra accumulation was modeled (Biass et al., 2014).

Volcano	Modeling strategy	Reference eruption	Column height (km a.s.l)	VEI	Eruption duration
Eyjafjallajökull	LLOES	2010	2.5–7.8	2	40 days
Hekla	ERS	2000	16.0–30.0	2	0.5–1 h
Hekla	ERS	1947	6.0–16.0	3	0.5–1 h
Katla	LLERS	Historical moderate/large	10.0–25.0	–	1–4 days
Askja	OES	1875 (C + D phases)	22.8–26.0	5	1 h + 1.5 h (C + D phases)

patterns. Scenarios used in this work are not associated with a probability of occurrence, due to the high uncertainties of such an approach. Thus, probabilistic hazard maps represent the expected situation conditioned to the occurrence of the scenario, i.e., the probability of having critical tephra load at a given point if the considered scenario occurs. Probabilistic hazard maps were computed for tephra load thresholds of 1, 10 and 100 $kg\,m^2$, which correspond to approximately 0.1, 1 and 10 cm of accumulation on the ground. At a European scale, results are probabilistic hazard maps (giving the probability of "disruption") for ash mass concentration thresholds of 2 and 2×10^{-3} $mg\,m^{-3}$. The second value (corresponding to a negligible mass concentration) was considered in order to estimate the impact in the case of a zero-ash-tolerance criterion. Moreover, Biass et al. (2014) provide maps of disruption mean persistence (according to Sulpizio et al., 2012) and arrival times for the 2 $mg\,m^{-3}$ concentration threshold. The main findings from the hazard assessment are (scenarios and their acronyms are described in Table 1) as follows:

- A 10-year recurrence rate eruption of Hekla (i.e., Hekla ERS 2000 type) only produces significant tephra accumulation close to the vent and in the southern part of Iceland. Ash concentration has a low probability ($< 1\,\%$) of exceeding the threshold of 2 $mg\,m^{-3}$ at any flight level (FL) in the UK airspace.

- A 100-year recurrence rate eruption of Hekla (i.e., Hekla ERS 1947 type) produces substantial tephra accumulation in the southeastern part of Iceland. However, far-range ash concentrations still have low probabilities ($< 5\,\%$) of affecting the UK airspace, with concentrations above the 2 $mg\,m^{-3}$ threshold at any FL.

- A moderate long-lasting basaltic eruption of Katla (i.e., Katla LLERS with tephra production over 1–4 days) is likely to produce substantial tephra deposition in southern Iceland. Ash dispersal has a substantial probability of reaching northern Europe, the UK (5–20 %) and central Europe ($\sim 5\,\%$) with concentrations exceeding 2 $mg\,m^{-3}$ at any FL.

- An eruption of Askja similar to that of 1875 (i.e., Askja OES 1875 type) is likely to produce massive tephra deposition in eastern Iceland. Ash dispersal has a substantial probability of reaching northern Europe, the UK (5–20 %) and central Europe ($\sim 5\,\%$) with concentrations exceeding 2 $mg\,m^{-3}$ at any FL.

- An eruption of Eyjafjallajökull similar to 2010 (i.e., Eyjafjallajökull LLOES 2010 type) is likely to produce moderate tephra accumulation south of the volcanic edifice around the town of Vìk. For computational reasons, probabilistic approaches to assess the airborne concentration resulting from such a long eruption were not applied.

Finally, in order to compare the relative impact of the different scenarios, one historical eruption was selected for each volcano for which ash dispersal and atmospheric concentrations were assessed using the same wind conditions of the Eyjafjallajökull 2010 eruption. The selected eruptions include Hekla 1947, Katla 1918, Eyjafjallajökull 2010 and Askja 1875. The conclusion is that all eruptive events, if they were to occur, would likely disrupt the European air traffic, with the most important perturbations caused by eruptions like Katla 1918 and Hekla 1947.

3 National-scale vulnerability and impacts

3.1 Exposed targets

In order to assess vulnerability and estimate potential impacts of tephra fallout in Iceland, one needs first to identify the "social, economic, environmental or cultural assets in areas that may be impacted by a hazard" (Birkmann, 2013, p. 305). The main exposed targets have been identified based on the scientific literature on tephra fallout impacts. In detail, the exposed targets that we consider are as follows:

1. *Population*: Iceland has 320 000 inhabitants, of which 120 000 live in Reykjavìk, the capital. About 60 % of the total population lives in the so-called Greater Reykjavìk (Supplement Table S1). Recent trends (Byggdastofnun, 2012) show that the population is growing around the

capital and in the eastern part of the country, where tephra fallout has high probabilities of occurrence for some of the eruption scenarios considered (Biass et al., 2014). The central part of the island is mostly uninhabited. Approximately one-quarter of the population has reduced mobility: 15 % of inhabitants are under 10 years old and 9 % are over 70 (Statice, 2012). This segment of the population is potentially more exposed to suffering respiratory difficulties due to the presence of suspended PM_{10} (Baxter et al., 1983; Horwell and Baxter, 2006). In addition, all of the population is exposed to indirect impacts due to failure of services (water and electricity supply, transportation, access to health care). Data on population for each municipality and percentage of exposed people are available in Table S2 in the Supplement.

2. *Emergency facilities, (e.g., hospitals, emergency shelters, police and fire stations)*: the two main Icelandic hospitals are located in Reykjavìk, but other hospitals and local health centers, also considered in our analysis, exist in relevant towns such as Akureyri, Isafjordur, Nordfjordur and Selfoss. Police and fire stations are quite well distributed amongst the main towns. Finally, shelters are usually public buildings located close to areas of interest (monuments, touristic attractions) and towns, but for simplicity we only consider schools as possible shelters.

3. *Mobility network (e.g., road network and mobility nodes such as ports and airports)*: the road network is directly exposed to tephra fallout, which may disrupt traffic, reducing the capability of the population to reach critical facilities and indirectly affecting services and productive activities. In the absence of a railway network in Iceland, the road network is extremely important for internal mobility. A main primary road circles Iceland along the coast. Disruption of the mobility network, even if temporary, can trigger relevant cascade effects. Ports are extremely important for the import/export activities in Iceland. In 2006, a total of 6 Mt of freight passed through Icelandic ports, which mainly export marine products (25 %) and import/export "other goods" (49 and 51 %, respectively), including textiles and manufacturing goods (Statice, 2012). Finally, airports are also important mobility nodes. The main airport in Iceland is Keflavìk, which accounts for more than 97 and 99 % of international passengers and freight traffic (Isavia, 2012), respectively. Important airports for domestic routes are Reykjavìk and Akureyri, accounting for approximately 25 and 50 % of domestic passengers and 47 and 20 % of freight (goods and mail), respectively (Isavia, 2012). Other smaller airports, including Egilsstadir, account for 12.5 % of domestic traffic of passengers. The volume of the domestic air traffic is modest (around 800 000 passengers per year; Isavia, 2012) but nonetheless important for the national economy, given the absence of a railway.

4. *Electricity network*: the electricity network is a critical infrastructure for economic activities and society in general. Electricity networks are very vulnerable to volcanic fallout (Wilson et al., 2009a, 2011), and consequences of a disruption of power generation and distribution are potentially dramatic. In Iceland, around 85 % of the primary energy is produced domestically from renewable energy sources. In 2011, electricity was produced almost entirely from hydroelectric (73 %) and geothermal (27 %) plants. More than 30 hydroelectric plants are spread across the country, except in the southern area of the Vatnajökull ice cap (Icelandic National Energy Authority, 2012a), and up to 7 geothermal plants are located around the capital and in the northeast (Icelandic National Energy Authority, 2012b). Some of them are combined heat and power plants, which utilize geothermal water and steam.

5. *Economic activities*: the main economic activities in Iceland are services and industry, which in 2011 employed 75.7 and 18.4 % of the working population, respectively (Landshagir, 2012). Comparison between Greater Reykjavìk and other regions shows that services in the capital region share a higher percentage of employees while industry dominates elsewhere (Landshagir, 2012). In particular, aluminum smelters are strategic components of the Icelandic economy, constituting 37.6 % of the total Icelandic exports and placing the country in the top-20 aluminum-producing nations worldwide. In 2011, aluminum smelting accounted for approximately 73 % of the gross electricity consumption (Landshagir, 2012).

6. *Agriculture*: the main agriculture activities are related to the production of wool and milk, which only account for a small percentage of the national GDP (Johánnesson, 2010). The distribution of the main agricultural areas (extracted from the Corine Land Cover raster map; see the Supplement Fig. S1) shows that a substantial part of the island is covered by snow and ice, and the few agricultural areas are barely visible and located in the proximity of main villages and coastal areas. Nevertheless, agriculture is important for local development, being the main economic resource for people living in small, isolated villages. Crops can suffer from short- to long-term impacts due to tephra accumulation (Wilson et al., 2009b). Fluoride absorption can impact cattle due to its toxicity and, unless direct inhalation is not a large concern, its ingestion through plants and water can cause diseases (Dawson et al., 2010).

7. *Water supplies*: Tephra fallout can disrupt water supply networks and water treatment plants (Stewart et al.,

2006). In Iceland, the areas close to active volcanoes are not densely populated and the disruption of water supply in urban areas seems not to be a large issue. However, tephra fallout can contaminate ground and surface waters, which are in some cases used for domestic/agricultural use (about a 95 % of the national water consumption relies on high-quality groundwater and only a 5 % on surface water; Gunnarsdóttir, 2012). This is usually the case for isolated farms, where no official quality controls are performed and, consequently, more are exposed to this hazardous phenomenon. Moreover, farms can suffer the indirect impact of tephra fallout on livestock, as it can contaminate water used for drinking (Wilson et al., 2009a; Dawson et al., 2010).

This list of exposed targets is not exhaustive but accounts for the main aspects generally considered in the literature. Amongst all these exposed targets, we selected the most significant for the national context based on practical considerations and data availability. Figure 2 shows maps of the considered features, based on several data sources: the national GIS data set (Landmælingar Islands, 2012), the European statistics database (Eurostat, 2013) and the Iceland National Statistics (Statice, 2012). In detail, Fig. 2a shows the location of the critical features considered (hospitals and schools that could be potentially be used as shelters), as well as the national road network. Our systemic vulnerability analysis is based on how easy it is for the population to reach critical facilities using the road network. Figure 2b shows the location of hydroelectric power plants and the electricity distribution network. The most densely populated areas and the main productive activities (aluminum smelters) are also displayed on the map. Figure 2c shows the location of mobility nodes relevant for the Icelandic socioeconomic system. Airports can be directly disrupted not only by tephra fallout but also by tephra dispersal in the atmosphere, which may cause airspace closure. Import/export activities at ports and airports can suffer indirect damage due to the disruption of the road network, power plants and productive activities.

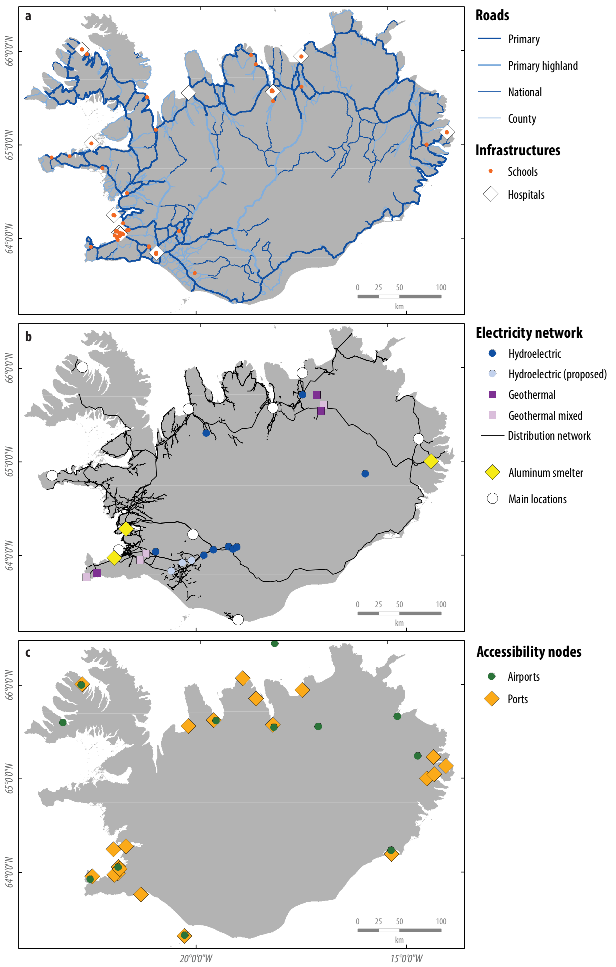

Figure 2. Exposure maps for **(a)** the road network and critical infrastructures (hospitals, local health care centers and schools, which can be used as ash shelters); **(b)** electricity distribution network, hydroelectric and geothermal power plants, production sites and main locations (urban areas); and **(c)** main transport nodes: ports and airport.

3.2 Vulnerability assessment

As mentioned, our vulnerability assessment focuses on the systemic and economic dimensions of vulnerability. This choice results from numerous factors, related partly to scientific and methodological aspects, including (i) the low probability of the exposed population suffering from relevant structural failure of buildings, and human casualties resulting from tephra accumulations suggested by the hazard analysis; (ii) the scale of the vulnerability and impact assessment (i.e., the whole country); (iii) the priorities for improving effective mitigation strategies in Iceland, defined through close cooperation between local stakeholders and the Icelandic Civil Protection; and (iv) the availability of accurate and up-to-date data. As a result, based on the different categories of exposed targets, we defined vulnerability themes and indicators (Table 2), focusing on the following aspects:

- physical vulnerability, limiting the analysis to electric power plants and distribution networks;

- systemic vulnerability, which refers to the interdependencies among exposed targets capable of reducing the overall functioning of the system itself and thus its capacity to react in the emergency phase following an event;

- economic vulnerability, which refers to the potential for temporary or permanent loss of economic activities and assets which are crucial for the Iceland economy and, consequently, for the maintenance of the level of

Table 2. Indicators (and estimators) defined for the systemic vulnerability from tephra fallout.

Category	Theme	Indicator (at municipality level)
Physical	Electric power plants and distribution network	Constant vulnerability = 1
Systemic	Accessibility	Travel time to critical facilities, energy production sites and mobility nodes
Socioeconomic	Agricultural areas	Combination of three factors: agricultural area, milk and wool production

welfare of the population. It is worth noting that economic activities (such as agricultural activities) or economic assets (industries, energy production sites etc.) can be indirectly affected by, for example, the interruption of transportation services.

Physical vulnerability has been quantified considering the hydroelectric power plants and the electricity distribution network due to their high vulnerability to tephra fallout (Wardman et al., 2012). Geothermal and combined-power plants are not considered because they are a priori much less vulnerable to tephra fallout given their thick reinforced concrete structure with few or no openings. We assign a vulnerability value of 1 to all exposed hydroelectric plants and aerial sections of the distribution network because detailed data to rank the vulnerability of each particular plant were not publicly available. The electricity distribution network has significant interdependencies with information infrastructures, other utilities and services, and economic activities (Pederson et al., 2006; Laprie et al., 2007; Beccuti et al., 2012). As a result, a disruption of hydroelectric plants and/or the distribution network may result in severe failures of dependent sectors, as demonstrated by the blackouts in Italy (2003) and Germany (2006), which impacted large areas of western Europe (Menoni and Margottini, 2011).

The systemic vulnerability assessment has been performed considering accessibility, which is a key issue during emergency situations. According to Bertolini et al. (2005), accessibility can be defined as “the amount and diversity of places that can be reached within a given travel time and/or cost”. During a crisis, bidirectional accessibility is crucial for both evacuating the population to safe areas and dispatching rescue teams (Galderisi and Ceudech, 2010). Although the disruption of the mobility networks due to tephra accumulation is generally temporary, it can result in significant cascade effects reducing accessibility to and from inhabited areas, emergency facilities, mobility nodes, power plants or industrial sites, with relevant consequences in terms of increasing losses and slower recovery. Here we consider the accessibility to emergency facilities (hospitals and shelters) for using the road network. The driving time is assessed using the Spatial Analyst toolbox in Esri ArcMap 10.2 (Esri, 2012). The hierarchy of the road network is accounted for

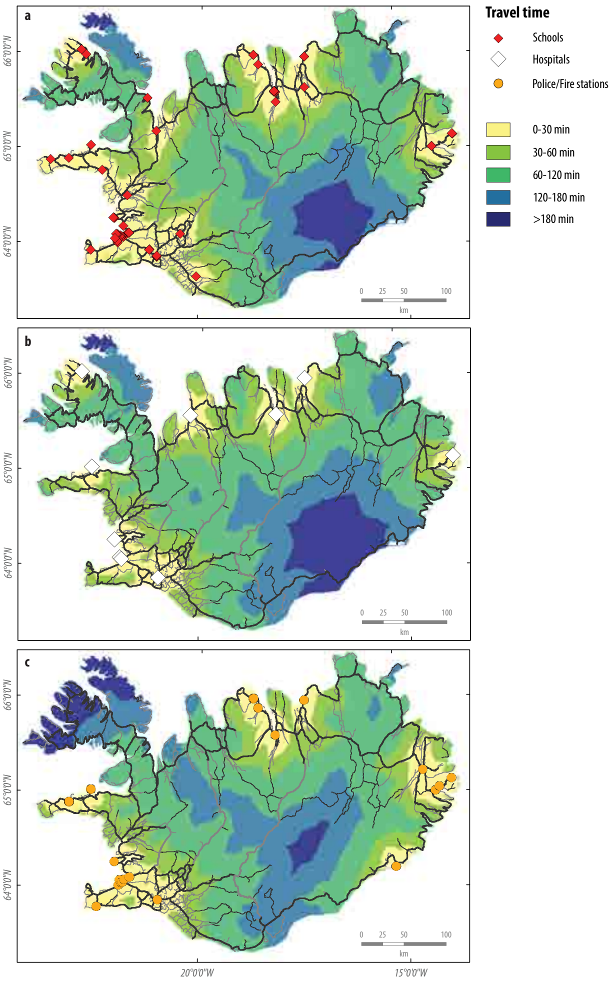

Figure 3. Accessibility to critical facilities: (from top to bottom) hospitals, schools and police/fire stations. All maps display the time in minutes required to reach a given facility by road.

using the official speed limits. Figure 3 shows the analysis of accessibility from inhabited areas to shelters, hospitals and fire stations. Based on this accessibility analysis we obtain the map of the most vulnerable areas.

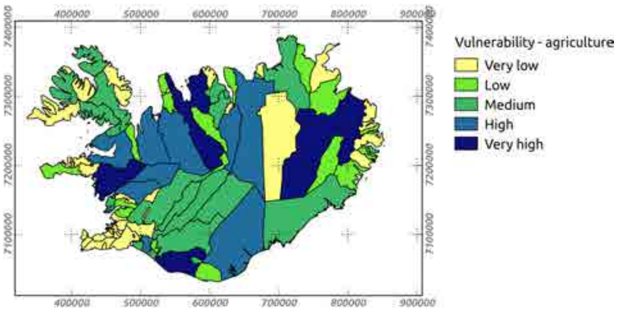

Figure 4. Thematic vulnerability map for agriculture. The five-class qualitative ranking is based on a combination of three indicators: production of milk, production of wool and percentage of agricultural area, all available at a municipality level. Maps for each indicator are given in the Supplement.

Finally, and given its complexity, quantity and diversity of data, the economic vulnerability assessment has been performed considering the agricultural sector only, assessing its relevance at a municipality level (Fig. 4). In order to estimate the importance of agricultural activities, we combine three different types of data: percentage of agricultural area, production of milk and production of wool. The percentage of agricultural area for each municipality was estimated by extracting pastures and crops from the CORINE Land Cover map (http://ec.europa.eu/agriculture/publi/landscape/about.htm), containing an inventory of soil use information at high resolution (100 m). The production of milk (L year^{-1}) and wool for each municipality during 2012 was provided by the Icelandic Regional Development Institute (Byggdastofnun, 2012). Wool production is expressed in terms of "support entitlements", i.e., the national entitlements that municipalities receive from the central government for their wool production and according to their percentage of the total production of the municipality (Á. Ragnarsson, personal communication, October 2012). Values of these three agricultural indicators have been classified in a five-class vulnerability ranking (very low, low, medium, high and very high vulnerability) using the natural breaks method (Jenks, 1967), commonly used in most GIS software and especially suitable for visualizing differences between classes (maps for each indicator are given in the Supplement Fig. S1).

3.3 Impact assessment

Before performing an impact analysis, it is necessary to determine the link between a quantitative hazard value (threshold) and each vulnerability indicator. Regarding the electricity network, there are two main impacts of tephra fallout: collapse/failure of network elements and flash-over of components. Wilson et al. (2011) define critical values of ash deposition for infrastructures based on well-documented impacts of past eruptions, and propose the value of 10 cm as a threshold for producing medium to high damages on network elements (towers, poles and lines). Moreover, Wilson et al. (2011) show that collapse of lines has happened for tephra fallout of a similar magnitude, while impacts on transformers can happen for lower fallout values. There is little evidence of impacts on power plants, but it is known that tephra fall is likely to cause disruption or shutdown (Wardman et al., 2012). In particular, coarse ash is more likely to cause tephra-induced abrasion on turbines, whereas a deposition of fine ash as thick as 50–100 mm may not cause strong abrasion. Moreover, in hydroelectric plants, tephra can engulf water channels and affect the turbines, limiting power plant functionality. Finally, Wardman et al. (2012) show that lower values of tephra fallout (5–10 mm) can cause tephra-induced insulation flash-over of components and provide a fragility curve for such a phenomenon. Thus, in order to include all effects, and according to the fragility curve, we assume that 1 cm tephra fallout has a 60 % probability of causing disruptions of components. It is worth mentioning that we used a fragility curve for wet tephra, adopting a conservative approach, while dry tephra is not likely to produce flash-over.

Regarding the road network, tephra depositions > 1 mm ($\sim 1\,\mathrm{kg\,m^{-2}}$) can cause a lack of visibility and disorient drivers, and can cause significant damage to vehicles' components and eventual engine failure (Wilson et al., 2011). However, this value does not take into account differences in road design, typology of vehicles, and other aspects such as a population's preparedness and coping capacity, which are becoming an important element in risk analysis (Frischknecht et al., 2010). In the case of Iceland, critical deposition thresholds for road disruption could be considerably higher due to the characteristics of the fleet of vehicles and the resilience of the population, who are used to coping with road traffic disruptions during winter snowfalls. We assume that a moderate disruption of the road network may happen with $\sim 10\,\mathrm{kg\,m^{-2}}$ tephra accumulation, while $100\,\mathrm{kg\,m^{-2}}$ would cause the total blockage of road transportation (Biass et al., 2012). Finally, we consider that an accumulation of 1 cm ($\sim 10\,\mathrm{kg\,m^{-2}}$) can cause damages to agriculture and impact livestock (Wilson et al., 2009a; Biass et al., 2012), as has occurred during past eruptions in Iceland (Thorarinsson and Sigvaldason, 1971; Gudmundsson et al., 1992; Höskuldsson et al., 2007).

Overlapping probabilistic hazard maps with vulnerable features allows for the identification of potential impacts, which is conditioned to the occurrence of the considered eruptions (Biass et al., 2014). We estimated the number of power plants and the total length of the electricity network with respect to 5, 10 and 20 % probabilities of being impacted (i.e., covered by a critical tephra load $> 10\,\mathrm{kg\,m^{-2}}$) if each scenario were to occur. Impacted features are identified by performing a GIS-based overlap of a probabilistic hazard map and an exposed target map (Fig. 2b). We assume that vulnerable parts of the network (Sect. 3.2) covered by

Table 3. Estimated impacts on electricity generation and distribution systems for different eruptive scenarios. For each eruptive scenario, we calculated the length of the electricity distribution system and the number of power plants having 5, 10 and 20 % probability of being affected by a critical ash fallout of 10 kg m^{-2}. Note that the 1947-type Hekla ERS has the highest impact on power plants due to the location of the volcano, close to five power plants.

Probability (%) for 10 kg m^{-2}	5	10	20	5	10	20
Eruptive scenario	Length impacted (km)			Number of power plants		
Hekla EES	0	0	0	0	0	0
Hekla ERS	500	263	106	6	5	4
Askja OES	1400	655	109	5	4	1
Katla LLERS	671	267	135	6	4	0
Eyjafjallajökull LLOES	207	122	73	2	0	0

tephra load greater than 10 kg m^{-2} (i.e., approximately 1 cm thickness) are expected to be disrupted, and contribute to the systemic damage. Impacts of lower tephra fallout values are not considered here, also accounting for the fact that not all components are necessarily directly exposed to tephra fallout. Expected impacts are displayed in Table 3. We partially account for the uncertainties related to the critical threshold choice by varying the probability of overpassing it between 5 and 20 % (Tables 3 and 4). Note that Katla has a high impact on power plants at any value of probability considered, due to its close proximity to five power plants. Moreover, tephra fallout from a Hekla 1947-type eruption can impact important electricity lines that connect power plants to the rest of the network, while the occurrence of a Hekla 2000-type scenario has a low probability (< 5 %) of impacting power plants and electrical infrastructure. Both the Hekla 1947 and the Katla scenario have a high probability (up to 20 %) of impacting important power lines that bring electricity to the southeastern region. An eruption at Eyjafjallajökull similar to that of 2010 could also impact these power lines (with a 10 % probability). Finally, in the event of an 1875-type eruption at Askja, power lines may also suffer strong impacts. The occurrence of such a scenario may in fact disrupt an important line that connects the eastern part of the country with geothermal and hydroelectric power plants located in the north and provides electricity to an important aluminum smelter (Fig. 2b). Note that, although a Hekla 2000-type eruption does not seem to affect any power plant, Biass et al. (2014) show that low tephra accumulations (~ 1 kg m^{-2}) can be produced in the area surrounding the volcano, and thus the possibility of having impacts due to a Hekla 2000-type scenario should not be discarded.

Biass et al. (2014) show that, if the considered eruptive scenarios defined for Katla and Askja were to occur, the probability of having tephra deposition of 10 and 1 kg m^{-2} in southern Iceland (ranging between 20 and 50 %) is substantial, while in eastern Iceland it is somewhat lower (5 to 20 %). Thus, agricultural activity in these areas can be impacted and livestock can suffer from fluorine intoxication due to water and soil contamination. We estimated the area devoted

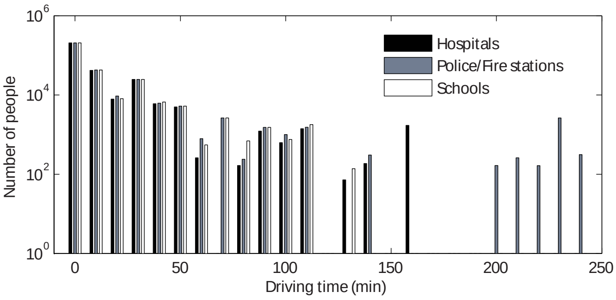

Figure 5. Number of people as a function of driving time to reach the closest critical infrastructures (i.e., hospital, police/fire station and schools).

to agricultural activities that has 5, 10 and 20 % probability of being impacted (i.e., covered by a critical tephra load > 10 kg m^{-2}) in the case of each eruptive scenario occurring. Results are summarized in Tables 4 and 5 and can be compared with the corresponding tephra accumulation hazard maps and vulnerability maps (Fig. 4 and Supplement Fig. S1). The highest impacts on crops are caused by the occurrence of the considered LLERS at Katla, followed by a 2010-type LLOES at Eyjafjallajökull, while pastures are expected to be particularly impacted in the case of an 1875-type OES at Askja and the considered LLERS at Katla. A 2000-type ERS eruption at Hekla is not likely to impact agricultural activities.

Impacts are also estimated on the basis of the accessibility analysis using least-cost-distance models (Wood and Schmidtlein, 2012). Using the census contained in the official GIS database (i.e., polygons of inhabited areas; Landmælingar Islands, 2012), we calculated the size of the population located in areas classified in terms of travel time (Fig. 5) to critical facilities: schools (Fig. 3a), hospitals (Fig. 3b) and police/fire stations (Fig. 3c). The Spatial Analyst toolbox of the ESRI ArcMap 10.2 software was used to calculate the shortest travel time from any pixel on the map to reach a critical facility using the road network. The hierarchy of the official road network (Landmælingar Islands, 2012) and the

Table 4. Estimated impacts on agricultural activities for different eruptive scenarios. Area of crops and pasture having 5, 10 and 20 % probability of being affected by a critical ash fallout of 10 kg m^{-2}. Katla LLERS and Eyjafjallajökull LLOES 2010-type scenarios cause the greatest impacts on crops, while pastures are particularly affected by eruptions of types Askja OES 1875 and Katla LLERS.

Probability (%) for 10 kg m^{-2}	5	10	20	5	10	20
Eruptive scenario	Crops impacted (km^2)			Pastures impacted (km^2)		
Hekla EES	0	0	0	0	0	0
Hekla ERS	10	0	0	281	13	0
Askja OES	10	1	0	586	287	26
Katla LLERS	14	7	1	361	125	101
Eyjafjallajökull LLOES	12	9	7	12	9	7

Table 5. Indicators (and estimators) defined for systemic vulnerability of the European air traffic system to tephra dispersal.

Vulnerability category	Vulnerability theme	Vulnerability indicator	Vulnerability estimator
Systemic relevance of features		Airports (all of Europe and northwestern Europe)	Passengers (n day^{-1}) Good (t year^{-1})
		Routes (all of Europe)	Number of average daily connections
		Main Routes (northwestern Europe)	Passengers (n day^{-1}) Goods (t year^{-1})
		Airspace sectors (FIRS, all of Europe)	Traffic rate per FIR
Socioeconomic	Air traffic and development	Population	Population/NUTS-2
		Air traffic	Goods/NUTS-2 passengers/NUTS-2
		Accessibility	Multi-modal accessibility/NUTS-2

speed limit for each road class were respected and implemented in a cost raster for accessibility analysis.

4 European-scale vulnerability and impacts

As clearly demonstrated during the Eyjafjallajökull eruption in 2010, the European air traffic system is largely vulnerable to loss of functionality of its elements when exposed to volcanic ash. The magnitude of systemic impacts depends on the relevance of the disrupted elements, and impacts of ash clouds can occur very far from the source (Ceudech et al., 2011). Here, we analyze the systemic vulnerability of European air traffic system and the socioeconomic vulnerability of the areas hosting its main airports.

4.1 Exposed targets

We define vulnerability indicators based on the analysis of European air traffic system, including main exposed airports and aviation routes. The analysis is performed at the European scale, but we focus on those regions where our hazard assessment indicates that impacts from ash dispersal can be significant.

The European air traffic network has more than 2000 international airports handling approximately 170 000 overall daily flights on average (Wegner and Marsh, 2007). However, over 50 % of the European air traffic is concentrated in the top 35 airports (Wegner and Marsh, 2007). The European air traffic network is scale-free (Wilkinson et al., 2001), meaning that these main hubs are the most relevant to the system, and therefore highly vulnerable to its failure. The main European hub is London Heathrow, with 61 million terminal passengers on international flights in 2010 (Heathrow Airports, 2013), followed by Paris Charles de Gaulle. The five London airports (Heathrow, Gatwick, Stansted, Luton and London City) account together for more than 60 % of the total number of UK passengers according to the UK Department of Transport. In 2011, London's airports handled more than 120 million passengers and 1.7 Mt of freight (CAA, 2012). Moreover, the most intense freight traffic in Europe during 2009 was between the UK and four European states: Germany, Netherlands, France and Belgium (PricewaterhouseCoopers, 2011). The London area is therefore one of the most critical and strategic points within the European air traffic network, and the airspace between London, Paris, Frankfurt and Amsterdam constitutes the densest part of the European civil aviation network. It therefore follows that the European air traffic network is particularly vulnerable to the failure of some of these strategic hubs.

At a national level, Keflavík airport is also strategic for the Icelandic economy. In 2011, Keflavík handled 97.5 % of all international passengers (1.75 million; Keflavík International Airport, 2012), 49.2 % of domestic passengers (0.75 million), and more than 99 % of all cargo operations. Air-based commercial relationships with Europe are very important for the Icelandic socioeconomic system. In fact, the European Economic Area market (i.e., the 27 EU countries plus Iceland, Norway and Liechtenstein) accounts for 82.7 and 61.9 % of total Icelandic exports and imports, respectively. The main commercial partners are Netherlands, Germany, the UK, and Norway. Iceland's imports come mainly from Norway, USA, Germany, Netherlands and the UK (Statice, 2012). According to the 2011 statistics, Keflavík's most important passenger destinations were Copenhagen, London and Oslo. During the period of 2010–2011 the Icelandic airspace experienced a 9 % growth in traffic (counting overflights) (Isavia, 2012), and, although peripheral in the European network, it is strategic for intercontinental flights from and to the USA and Canada. Disruption of air traffic connections can therefore substantially impact on both local and regional economies.

Based on these considerations, the exposed targets for our systemic vulnerability analysis are the main airports and routes to north and central Europe and the most relevant socioeconomic features of the areas where the main airports are located. In order to have a vulnerability assessment meaningful to civil aviation stakeholders, we consider European airspace sectors, following the current classification (EUROCONTROL, 2005). Flight Information Regions (FIRs) are subdivided according to their specific role into CTA (control area), OCA (oceanic control area), ACC (area control center) and UAC (upper area control), which are airspace sectors not hosting airports (EUROCONTROL, 2005). Aerial sectors represent a key component of the air traffic network because each sector has an associated capacity, which is the main parameter for air traffic management (Leal de Matos and Ormerod, 2000; Leal de Matos and Powell, 2002; Dell' Olmo and Lulli, 2003).

Finally, we note that the territorial context of an airport is also relevant for the estimation of socioeconomic vulnerability and impact because the vulnerability of a region is proportional to its dependence on air traffic.

4.2 Vulnerability indicators

Table 5 summarizes the systemic and socioeconomic vulnerability indicators defined for the European air traffic system. Figures 6–10 show vulnerability maps produced for the considered features (airports, routes, airspace sectors and European regions). Visualization is performed through the open source GIS Qgis (http://www.qgis.org/en/site/), using the European GIS database (GISCO, 2013) and European air traffic database (courtesy of EUROCONTROL). Unless specified otherwise, all indicators are reclassified into a qualitative five-class ranking, ranging from very low to very high, using the natural breaks method (Jenks, 1967). Vulnerability indicators include the following:

1. Strategic airports. We assume that the higher the traffic of an airport, the higher its relevance and, consequently, the higher the vulnerability of the system to its potential disruption. We classified all European airports according to traffic of passengers and freight during 2012 (Eurostat, 2013), and this identified Frankfurt, London Heathrow, Amsterdam and Paris Charles de Gaulle as the strategic elements for the European air traffic system in terms of passengers and goods. Given that the probability of ash dispersal affecting southeastern Europe is low (Biass et al., 2014) and that we aim to assess the vulnerability within a more constrained domain, we performed the same analysis for central and northwestern Europe. Having selected the most relevant airports in central and northern Europe in terms of air traffic values (Supplement Table S3), we ranked them according to passengers and freight values (Fig. 6). The most relevant airports are London Heathrow, Paris Charles de Gaulle, Frankfurt, Amsterdam and Munich, which have already been identified as main hubs at the European level. Copenhagen airport also has a high relevance for traffic to northern Europe (including Iceland).

2. Strategic routes, classified in two ways. The first classification builds upon the average number of connections between each pair of European airports in 2012 (courtesy of EUROCONTROL). We assume that the higher the number of connections the higher the importance of the route and the higher the systemic vulnerability of the system to its failure. This classification reveals that the top five connections are Madrid–Barcelona (Spain), Istanbul–Izmir (Turkey), Paris–Toulouse (France), Oslo–Bergen (Norway) and Barcelona–Palma de Mallorca (Spain). Constraining the analysis to central and northwestern Europe, the most relevant connections are London–Paris, Paris–Frankfurt, London–Edinburgh, London–Dublin, Munich–Frankfurt, Copenhagen–Aalborg, Oslo–Trondheim, Oslo–Bergen and Oslo–Stavanger. This analysis underlines that the main city pairs are often composed of national connections between first- and second-largest cities, as described by Wegner and Marsh (2007). The second classification is based on air traffic (passengers and freight) for each city pair, i.e., for the main routes between a considered airport and its partners (Eurostat, 2013). This kind of classification considers the relevance of European routes for a selected sub-system constituted by the considered airport and its main European partners. For example, we show two relevant cases: the London

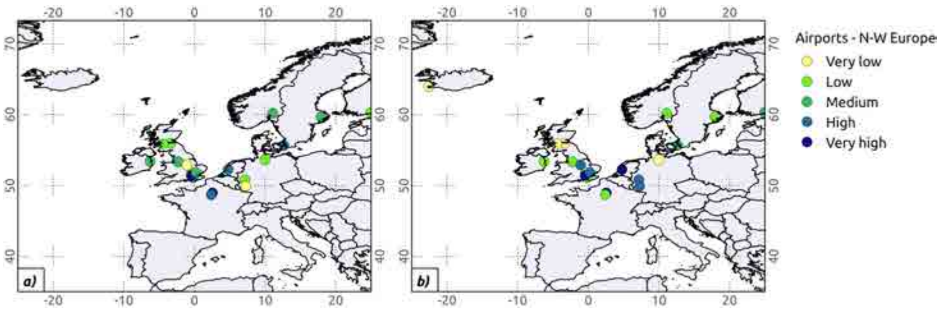

Figure 6. Main airport hubs in central and northwestern Europe depending on the traffic of passengers **(a)** and goods **(b)** during 2010 (Eurostat, 2012). The values represent the relevance of these airports for passengers and freight air traffic. The most relevant airports are London Heathrow, Paris Charles de Gaulle, Frankfurt, Amsterdam and Munich.

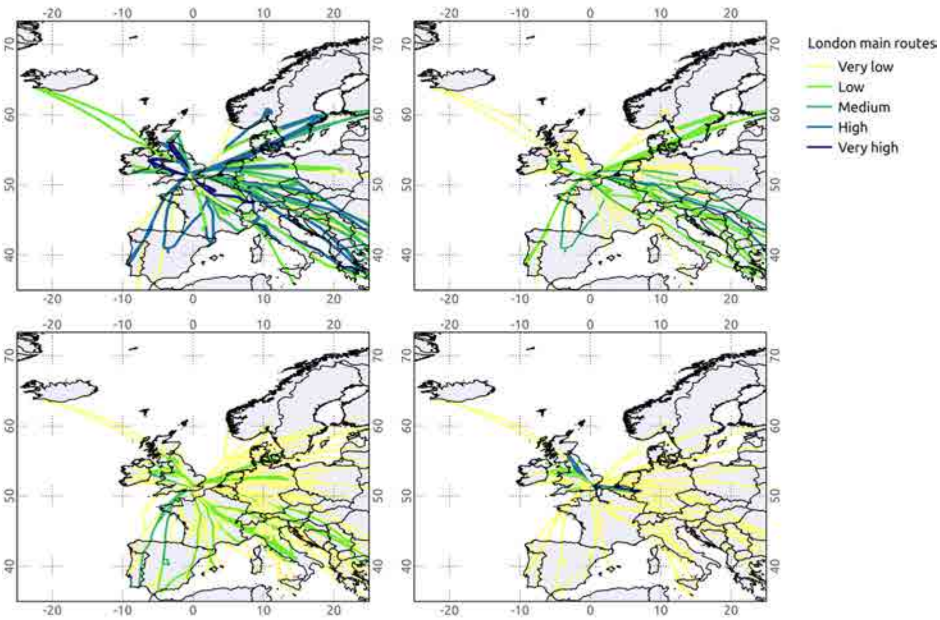

Figure 7. Main European routes from/to London Heathrow (top) and the rest of the airports in Greater London (Gatwick, Luton and Stansted, displayed together, bottom). Routes are ranked according to their importance in terms of passengers (left) and freight (right) traffic. The vulnerability classification is based on the whole range of air traffic data between main London airports and the considered European airports in 2010 (Eurostat, 2012). The same classification criterion is used for all figures and the comparison underlines that Heathrow airport handles the most strategic routes (corresponding to more than 1.2 million passengers per year).

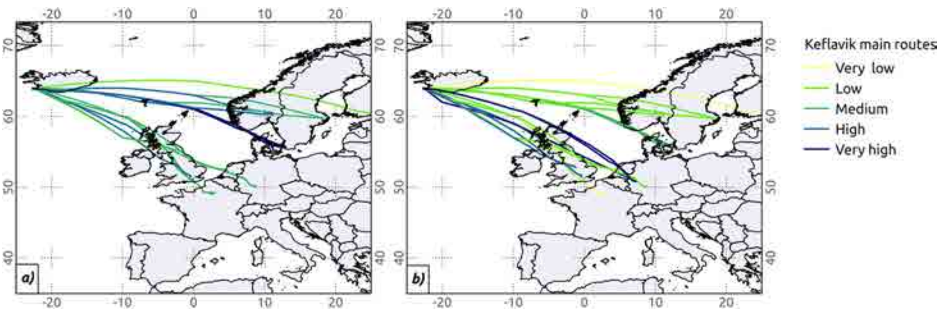

Figure 8. Main European routes of passengers **(a)** and freight **(b)** from/to Keflavík airport. Analysis is performed for the routes connecting the main airports shown in Fig. 6. The vulnerability classification is based on 2010 data (Eurostat, 2012).

hub, strategic for European air traffic, and Keflavík airport, the most important in Iceland. The relative importance of routes is a measure of the vulnerability of the sub-system to the disruption of that particular route. In our analysis, the London hub includes the city's four main airports: Heathrow, Gatwick, Stansted and Luton. Figure 7 shows strategic routes of London airports for passengers (left) and freight (right), for Heathrow airport (top) and for the other three airports, displayed together (bottom). The top London destinations (> 1.2 million passengers year^{-1}) are Dublin, Edinburgh, Paris and Frankfurt. London Heathrow–Dublin is the most important connection, with more than 1.5 million passengers per year. In terms of cargo, Stansted is also an important hub with main destinations to Frankfurt, Brussels, Stockholm and Paris. Figure 8 shows the most important partners for Keflavík airport in terms of passengers (a) and goods (b). Copenhagen, London and Oslo are strategic destinations for passengers, whereas Amsterdam, London, Paris, and Cologne–Bonn are main nodes for freight transportation. It is worth noting that the main passenger routes from Keflavík airport have the same order of magnitude as the less relevant route for the London hub ($\sim 300\,000$ passengers per year). Keflavík routes, if classified using the same range used for the London airports, would fall into the low-vulnerability class, and their relevance would be diminished in the subsequent impact analysis. Using a scale-dependent classification criterion allows for identification of routes that can be secondary at a broader European scale but are strategic for the national scale.

3. Number of daily European flights in each airspace sector, which gives a measure of the airspace congestion. For simplicity, our analysis uses data of one of the peak days during 2012 (29 June) and assumes that this particular day is representative of high-traffic situations in Europe. For each airspace sector, we counted how many times per day the sector is crossed by flights at any FL and assign a vulnerability value accordingly. Figure 9 shows that the most congested airspace sectors are located in France (Brest, Paris and Marseille FIRs), the southern UK (London FIR), Germany (Langen, Bremen and Hannover FIRs), Netherlands (Amsterdam FIR), and Italy and Spain (Milan, Rome and Madrid FIRs). Some FIRs show lower traffic rate compared to the surrounding areas, for example Ireland (Shannon FIRs) and other regions of France (Bordeaux and Reims FIRs).

4. Relevance of air traffic for European regions, based on a combination of four regional indicators: population (Eurostat, 2013, data from 2012); total number of passengers and tonnes of freight transported by air (Eurostat, 2013, data from 2011); and multi-modal accessibility, which takes into account the

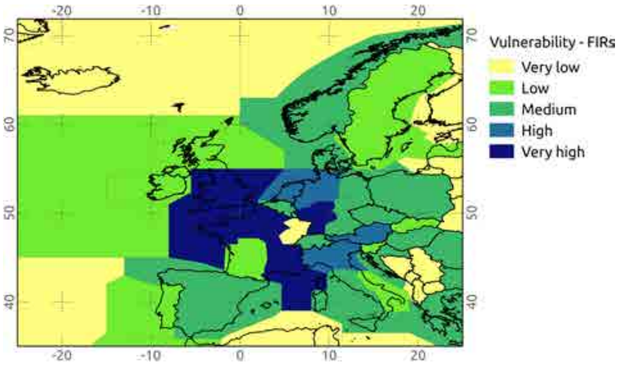

Figure 9. Vulnerability classification of the European airspace sectors based on the air traffic rate in the sector during a peak day of 2012 (source: EUROCONTROL, 2012). FIRs with very high vulnerability values (blue) are London, Paris and Munich.

presence/absence of alternative transport modes and their cost (ESPON, 2004; TRACC, 2010, p. 17). We use multi-modal accessibility produced by the ESPON project (ESPON©, 2013) as an indicator of vulnerability: areas with low multi-modal accessibility are therefore more vulnerable to the failure of one transportation mode due to the limited variety of alternative transportation modes available. According to Fürst et al. (2000), multi-modal indicators have much more explanatory power with respect to regional economic performance than any accessibility indicator based only on a single mode. We propose a first-level assessment of socioeconomic vulnerability by combining these four indicators under the assumption that vulnerability increases when the dependency on air traffic is higher and the multi-modal accessibility lower. All indicators refer to the 2003 NUTS-2 regions (Nomenclature of Territorial Units for Statistics), a hierarchical system for dividing the economic territory of the EU for the application of regional policies. We combine the four indicators by summing the values for each NUTS-2 region, and reclassifying the resulting map into five vulnerability classes. Population, air traffic and multi-modal accessibility are classified into five equal interval classes, while the multi-modal accessibility database produced by the ESPON project is already ranked into five qualitative classes, ranging from 1 (highly below average) to 5 (highly above average). Air traffic data show that the areas which most rely on air traffic correspond to the regions hosting the main European cities of London, Paris, Frankfurt and Amsterdam. But socioeconomic vulnerability is not only related to the volume of air traffic: for example, Ireland has a low multi-modal accessibility (Supplement Fig. S2) but a considerable population (Supplement Fig. S2). The resulting vulnerability map (Fig. 10) facilitates recognition of the

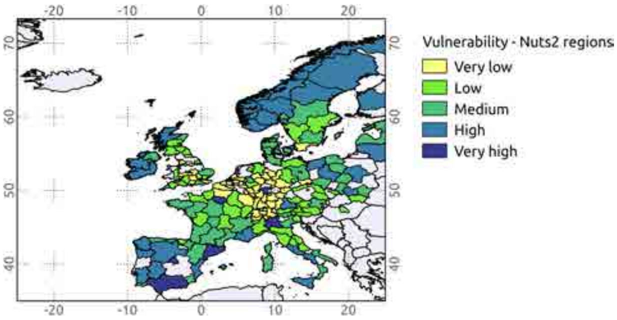

Figure 10. Vulnerability of the NUTS-2 regions, calculated as a combination of population, air traffic values and multi-modal accessibility value (see the Supplement Fig. S2 for individual maps). High-vulnerability areas are those having high population and low accessibility rates, for example Ireland and Norway.

areas most dependent on air traffic, where a relatively high population and/or air traffic values are associated with low multi-modal accessibility. The most vulnerable NUTS-2 areas are therefore the ones hosting the cities of London, Paris, Frankfurt and Amsterdam. Also, Ireland, Norway and northern France show a medium–high vulnerability. Due to the intrinsic nature of being an island, air traffic cannot easily be substituted by alternative transportation means. For this reason, Ireland has medium vulnerability to air traffic disruptions.

Given the differences in the indicators of vulnerability, we evaluate the expected impacts for each single vulnerability feature, i.e., for the national-scale assessment, we do not merge the different thematic vulnerability maps (Figs. 6–10) into a single map. However, once the strategic elements and their relevance are identified, it is possible to assess the expected impacts of each eruptive scenario through a GIS-based overlap of hazard and vulnerability maps.

4.3 Impact assessment

We propose three different methods for assessing the impacts of tephra dispersal on European air traffic. Each method focuses on producing specific results, and could be used to support risk management strategies at different levels. It should be kept in mind that impact assessment results are conditioned to the occurrence of the eruptive scenario (Biass et al., 2014).

The first method consists of a qualitative GIS-based visual overlap of hazard and vulnerability maps. The graphical overlap allows for an immediate identification of the routes that have the highest probability of being disrupted for each scenario. For example, the overlap of the Askja hazard map for all FLs and the main passenger routes between London Heathrow and Europe (Fig. 7a) reveals which routes would have the highest probability of being disrupted in this scenario. The overlap of hazard and vulnerability can also be performed using hazard maps for specific FLs and averaged arrival time and persistence maps, which allow for the potential duration of a disruption to be inferred.

The second method estimates the impact (movements disrupted, passengers and freight stranded) at given airports by multiplying the average atmospheric persistence time of a given hazardous ash concentration for a given eruptive scenario by the hourly averaged traffic. Here, we assume that, if the critical ash concentration is reached at any FL over an airport, all flight operations are disrupted. For example, Tables 6 and 7 show the expected impacts at London Heathrow and Keflavík airports for the different eruptive scenarios considered, respectively. Air traffic values for London Heathrow are estimated dividing yearly averages (CAA, 2012; Heathrow airport, 2013) by 365. Keflavík air traffic values are inferred from the Keflavík airport 2011 facts and figures document (Keflavík International Airport, 2011). According to Biass et al. (2014), the conditional probability of having more than 24 h of disruption at London airports from Askja 1875 and Katla 1918 scenarios is about 5 and 1 %, respectively. The conditional probability of having more than 24 h of disruption due to Hekla activity is lower than 1 %. Thus, there is a substantial probability of having strong disruptions in the London area due to high-magnitude explosive volcanic eruptions at Askja and Katla, and a low probability of having impacts at London due to lower magnitude events at Hekla.

Finally, the third method consists of overlapping hazard and vulnerability data and combining the values on a cell-by-cell basis, i.e., multiplying hazard and vulnerability values within each cell. To do that, hazard and vulnerability maps are converted to raster format (GeoTIFF) using GRASS GIS (Neteler et al., 2012). We use probabilistic hazard maps for each scenario that account for the probability of disruption at any FL (Biass et al., 2014) and vulnerability maps of the airspace sectors (Fig. 9). Such maps are then overlapped on a cell-by-cell basis and the resulting impact map is reconverted to vector format, aggregating the maximum impact value over FIRs areas. The final results are impact maps containing impact values for each FIR, reclassified into five qualitatively impact classes (very low to very high impact) using the natural breaks method. These results are shown in Fig. 11. It has to be stressed that the resulting impact represents relative comparison between FIRs rather than a quantitative impact. The Hekla ERS 2000-type scenario (Fig. 11a) produces very high impacts in the Reykjavík FIR, high impacts in the London FIR and low impacts in the Shanwick OCA and the Norway FIRs, but is not expected to affect central Europe. The Hekla ERS 1947-type scenario (Fig. 11b) produces very high impacts in the Reykjavík FIR, and Paris, Brest and Marseille FIR; high impacts in the London FIR; and low impacts in the Shanwick, Norway and Sweden FIRs. Such a scenario is also likely to result in low impacts in the northern Germany and Poland FIRs. Both the Katla LLERS (c) and the Askja OES 1875-type (d) scenarios are likely to produce high impacts in the Keflavík FIR as well as the southern UK and

Table 6. First-order estimation of expected impacts at London Heathrow airport for different eruption scenarios based on the averaged persistence. Air traffic values are based on yearly averages (CAA, 2012).

Eruptive scenario	Mean persistence all FLs (h)	Movements disrupted (n)	Passengers stranded (n)	Freight stranded (t)
Hekla-2000 ERS	∼ 3	∼ 160	∼ 23 000	∼ 600
Hekla-1947 ERS	∼ 4	∼ 180	∼ 27 000	∼ 700
Katla LLERS	∼ 10	∼ 530	∼ 78 000	∼ 2000
Askja OES	∼ 8	∼ 410	∼ 60 000	∼ 1500

Table 7. First-order estimation of expected impacts at Keflavík airport for different eruption scenarios based on the averaged persistence. Air traffic values are based on the Keflavík airport 2011 facts and figures document (Isavia, 2012).

Eruptive scenario	Mean persistence all FLs (h)	Movements disrupted (n)	Passengers stranded (n)	Freight stranded (t)
Hekla-2000 ERS	∼ 5	∼ 20	∼ 950	∼ 20
Hekla-1947 ERS	∼ 8	∼ 30	∼ 1500	∼ 40
Katla LLERS	∼ 21	∼ 90	∼ 4300	∼ 110
Askja OES	∼ 18	∼ 70	∼ 3600	∼ 90

France FIRs, mostly due to their high traffic rates (and therefore high vulnerability). These scenarios can also produce high impacts in the Norway, Sweden, Austria and Germany FIRs. Low impacts are expected in the rest of Europe.

5 Discussion

Outcomes of our impact assessment are derived from probabilistic analysis, which are conditioned to the occurrence of specific eruptions at specific volcanoes described in the hazard scenarios of Biass et al. (2014). Volcanoes were selected based on the probability of eruption and significance of associated impact, while the hazard scenarios were derived from field observations to be statistically representative. However, an eruption at a different volcano or a different type of activity at the selected volcanoes cannot be excluded, and therefore the impact in zone other than those identified in our assessment cannot be discarded. The main value of our work is the new multi-source, multi-scale strategy introduced to assess both hazard and impact at different scales that can be easily applied to other volcanoes and other hazard scenarios. Nonetheless, considering the wide range of hazard scenarios investigated and the statistically representative meteorological conditions analyzed at the European scale, our hazard and impact assessments can be considered as a first-level evaluation for the whole Icelandic region.

5.1 National-level vulnerability and impact assessment

The methodology presented here to assess vulnerability to tephra fallout at a national scale was developed for the particular case of Iceland in cooperation with local stakeholders and the Icelandic Civil Protection Department, and uses only publicly available data. However, the method could potentially be applied in different geographic and socioeconomic contexts where similar public censuses are available. The list of exposed features identified in Sect. 3.1 is valid elsewhere and Table 8 lists the type of data that, ideally, should be included in any comprehensive vulnerability assessment. For example, from a socioeconomic point of view, the role of productive activities and the number of employees for activity or sector should be taken into account. Industrial and tertiary activities, for example, often constitute the backbone of the socioeconomic system, driving local development and distribution of resources. In terms of transportation, one inconvenience is that national statistics are rarely given by transport mode, making it difficult to identify the precise contribution of air traffic to the socioeconomic system. Also, water supply has been recognized as an exposure target in a few isolated cases (Sect. 3.1) but is not taken into account for the estimation of impacts, because it needs to be treated at a more local scale. A census of water supply systems (for example, water quality control and monitoring) may support response strategies, in particular for areas with strong agricultural sectors (Fig. 4) that can suffer substantial impacts from tephra fallout (Sect. 3.3). Finally, only a few data sets were available at a municipality level or in the form of disaggregated data (that is, data available at the same administrative level used for collection). For example, most economic and labor market indicators were produced at the national level. This lack of disaggregated data is a common problem in most risk assessments, and the availability of disaggregated data sets, or data sources defined at lower administrative levels, would improve the vulnerability assessment presented here.

Figures 3 and 4 allow for the spatial distribution of the most vulnerable areas and targets to be identified according

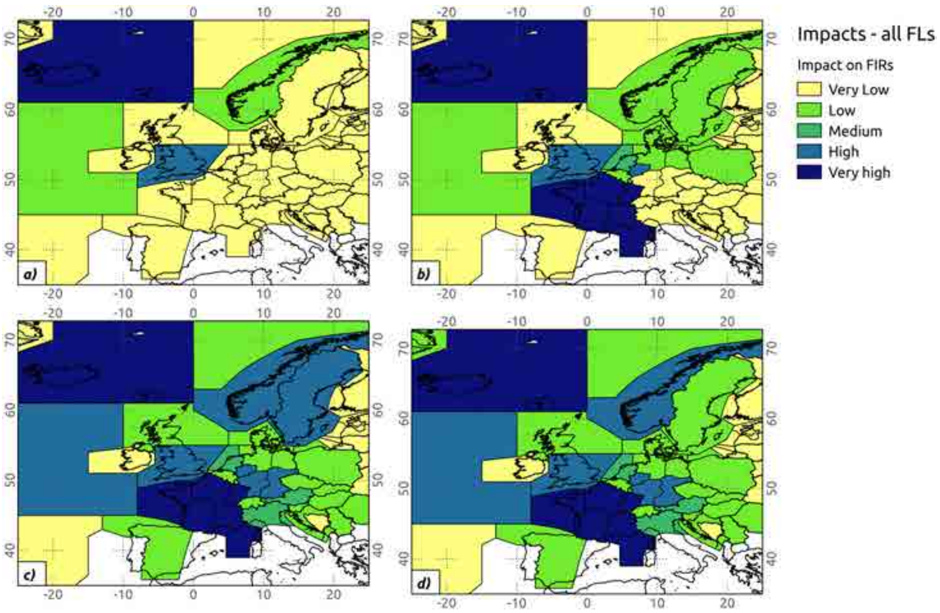

Figure 11. Expected impacts of tephra dispersal on European airspace sectors (FIRs) if the different scenarios considered were to occur: **(a)** Hekla 2000 type, **(b)** Hekla 1947 type, **(c)** Askja 1875 type and **(d)** Katla scenarios.

Table 8. Availability, sources and type of data used for the vulnerability assessment to tephra fallout at the national scale.

Data	Available	Source	Coverage	Type
Population	Yes	Statice	Municipalities	Number
Population trends	Yes	Byggðastofnun	Municipalities	Percentage
Population age	Yes	Statice	Municipalities	Number
Power plants	Yes	Landmælingar Islands http://www.or.is/en/about	Disaggregated	Location
Aluminum smelters	Yes	Landmælingar Islands	Disaggregated	Location
Hospitals	Yes	Landmælingar Islands	Disaggregated	Location
Shelters	Yes	Landmælingar Islands	Disaggregated	Location
Police stations	Yes	Landmælingar Islands	Disaggregated	Location
Fire stations	Yes	Landmælingar Islands	Disaggregated	Location
Road network	Yes	Landmælingar Islands	Disaggregated	Digital map
Electricity network	Yes	Landmælingar Islands	Disaggregated	Digital map
Ports (import/export)	Yes	Statice	Disaggregated	Import/export values
Airports (air traffic)	Yes	Isavia	Disaggregated	Passengers/freight values
Land use	Yes	Corine Land Cover	Homogeneous areas	Corine classification
Milk production	Yes	Byggðastofnun	Municipalities	Liters/support entitlements
Wool production	Yes	Byggðastofnun	Municipalities	Support entitlements
Civil protection units	No	–	–	–
Productive activities	No	–	–	–
Employees for productive activities/sectors				
Average income	No	–	–	–
Water supply	No	–	–	–

to the considered vulnerability themes. It is important to stress that the vulnerability scores, expressed either as numerical scores or qualitative judgments, normally represent comparative (i.e., relative) values. This makes the merging of different vulnerability maps into a single final map a complex process. On the one hand, the perspective of single indicators can be lost when combined with others. On the other hand, single merged maps are more synthetic and workable if they involve no loss of information. In this work, and given the very different nature of the indicators considered, we prefer not to overlap maps of different vulnerability categories. Nonetheless, the comparison of information related to each vulnerability indicator can provide a significant support both to land use and emergency planning.

Results from national vulnerability and impact assessments allow for definition of priority areas for risk mitigation strategies. Comparison of population values with other vulnerability indicators can support the prioritization of interventions for long-term vulnerability mitigation plans. For example, northeastern Iceland has a substantial probability of being affected by deposition of tephra in the case of an OES occurrence at Askja, and this hazardous phenomenon should be considered in long-term territorial plans. Recent population statistics (Byggðastofnun, 2012) show a positive trend in this area due to the construction of a dam and the consequent generation of employment. The increase in population and the arrival of non-local workers, less familiar with an active volcanic environment, should be taken into account, e.g., through educational programs. The results of the impact assessment can also support Icelandic policies in the main strategic sectors such as transportation, economic activities or location of critical facilities. Table 3 shows that the largest impacts are expected from the occurrence of selected eruptive scenarios (Table 1) at Askja, Katla and Hekla, due to the presence of power plants and a main power line in their surroundings. Results suggest that moderate tephra fallout from a 1947-type ERS at Hekla can have major impacts on the surrounding power plants. Occurrence of low-magnitude 2000-type ERS activity at Hekla does not seem to produce such major impacts but, given its very high frequency (10-year repose time; Höskuldsson et al., 2007), should also be taken into account. In fact, repeated tephra fallout could have long-term impacts on power plant equipment and external components. Expected impacts on agricultural activities are in general limited to the few crops located in the southeast of the island. Table 4 shows that the major impacts on crops are expected in the case of an LLERS at Katla and a 2010-type LLOES at Eyjafjallajökull. Moreover, ash fallout from the occurrence of eruptive scenarios at Askja and Katla is expected to cover several square kilometer of pasture in the south and east of Iceland (Table 4). Due to the importance of agricultural activities (wool in particular) for the Icelandic economy, these results should be taken into account in order to improve preparedness and reduce impacts on the national socioeconomic system. Finally, results of the accessibility analysis (Figs. 3, 5) help the identification of zones with limited access to critical infrastructure by classifying the population in terms of travel time to strategic features (hospitals, police/fire stations and potential shelters). This analysis accounts for the travel speed of the road network, where pixels outside the road network are only allowed an average walking speed. Note that unlike agent-based strategies, the resulting model is time-independent and does not attempt to account for dynamic travel time costs due to route capacity or road congestion (Wood and Schmidtlein, 2012). However, least-cost-distance models still provide key information for preparedness and planning by identifying heterogeneities in the accessibility over the entire territory rather than modeling the behavior of individuals. A combined look at Figs. 1 and 3 highlights how most of the critical infrastructures are clustered around the main towns, with the main zone of low accessibility being the Vatnajökull area. Figure 5 is a combination of the analysis performed in Fig. 3 and the population census, and helps visualize the number of people as a function of the travel time to critical infrastructures. Figure 3c also shows that although uninhabited, Vestfjörður, the northwesternmost peninsula, has a low accessibility to police/fire stations. This is clearly reflected in Fig. 5, where a travel time greater than 3 h is associated with thousands of people. As a result, such a method is valuable to plan the implementation of additional critical infrastructures for future crises.

The analysis of impacts performed here is essentially qualitative. The underlying vulnerability assessment does not include a physical vulnerability analysis of the elements at stake, due to the limited availability of data at the scale of the analysis. The definition of critical ash load thresholds does not rely on fragility curves, instrument commonly recognized amongst the risk management community but having a very limited application to volcanology (ENSURE, WP 1 – Del. 1.1.1). In particular, fragility curves to tephra fallout are available for building typologies (associated with a given physical vulnerability), but are still not well characterized in the case of ash fallout on main infrastructures, for which there are many factors (composition, humidity) that play an important role (Wilson et al., 2011). In addition, ash load thresholds can vary with weather conditions. For example, wet tephra has a higher impact on electric components (Wardman et al., 2012) and enhances the effects of ash coverage on road traffic (Wilson et al., 2011). Wilson et al. (2009b) pointed out the seasonal character of vulnerability, an important factor for certain activities such as agriculture and farming that have a seasonal character (Jóhannesson, 2010). For example, the same hazardous phenomenon could have higher impacts on crops during the sowing, growth and flowering phases, while less impacts are expected on unplowed fields. Adapting thresholds to seasonal and weather variation would support the definition of specific seasonal strategies. Finally, we adopted the same threshold for all eruptive scenarios, ignoring that impacts can depend on many factors such as ash grain size and composition (Wilson et al., 2009b).

Even though we adopted different grain-size distributions for each eruptive scenario (Biass et al., 2014), no study exists on ash load threshold dependency on granulometry and composition. Identifying critical ash load thresholds with single values introduces limitations into the usage of results. But given that the main aim of this work is identifying the areas and features that are expected to be impacted, results can support detailed impact assessment analysis at specific areas, necessary in order to produce more reliable results. Nowadays there is a growing need for specific studies to be performed in order to define quantitative thresholds that produce physical damages of elements and, eventually, systemic impacts. In future, fragility curves would allow hazard intensity and probability of damage to be accounted for, and our impact assessment methodology would be developed accordingly.

5.2 Vulnerability and impact assessment of European air traffic

We have proposed a vulnerability assessment that identifies the elements (airports, routes and airspace sectors) likely to have major impacts on the European air traffic system in the case of tephra dispersal from eruption of an Icelandic volcano. London is recognized to be the core of the European aviation system, followed by Paris, Amsterdam and Frankfurt, according to the number of connections handled (Fig. 6). Our analysis has also identified the routes that have the highest socioeconomic relevance, constrained to central and northwestern Europe based on the outcome of the hazard assessment (Biass et al., 2014). The analysis emphasizes the role of minor connections that, despite being secondary at the European level, are strategic for national economies. For example, the analysis of air traffic at London and Keflavík airports showed that London–Dublin and Reykjavík–Copenhagen are very important routes (Figs. 7 and 8) and their disruption could affect national economies and those of their commercial partners. We also estimated vulnerability of FIRs (Fig. 9) based on traffic data from a peak day. This first-order estimation could be enhanced using air traffic data during a larger time interval to account for weekly/seasonal traffic variability. Moreover, other indicators for FIRs, for example accounting for the different types of flights (charter, commercial, business, cargo), could also be considered. Despite these methodological limitations, the identification of strategic airspace sectors is an important result itself given that current air traffic management procedures are based on airspace capacity (Cook, 2007).

The methodology proposed in this work is flexible enough to include new administrative boundaries and new procedures in the vulnerability assessment. This is important if, as expected, regulation changes occur. At a European level, new trends in air traffic management are driven by the Single European Sky Commission Project (SESAR, http://ec.europa.eu/transport/modes/air/sesar/), aimed at ensuring capacity and safety needs to European aviation. The SESAR program includes the constitution of functional airspace blocks (FABs), expected to be operative in the next few years, which would reduce airspace fragmentation and support integrated airspace management (Arroyo, 2008). In the case of ash-contaminated airspace, the new SESAR regulation framework could be included in the analysis to support the development of new centralized strategies. It has also been suggested that the short-term capacity of sectors may be negotiated in order to allow rerouting of flights to opened FIRs, thus improving the performance of the network. However, procedures to be adopted in the case of ash-contaminated airspace (e.g., the possibility of overflying ash clouds) are still under discussion. The idea that the airlines will be able to decide whether to fly or not in ash-contaminated airspace has been proposed by EUROCONTROL and implemented during the 2011 VOLCEX exercise, as described in the final report (ICAO, 2011). This new paradigm could be implemented in the EUR/NAT region by several stakeholders that, after the approval of a safety risk assessment (SRA; Bolić and Sivčev, 2011; EASA, 2012), would be able to decide whether to fly or not through ash-contaminated airspace sectors. The introduction of SRA underlines the importance of having a long-term perspective in risk-management procedures and plans. Long-term risk management plans could also avoid secondary impacts, e.g., the lack of fleet at non-contaminated areas during the closure of main airports. For example, Icelandair managed to move aircraft from Keflavík to a secondary hub in the UK (Ulfarsson and Unger, 2011) to maintain operations in non-contaminated areas (and, in particular, intercontinental routes). Long-term hazard assessment and vulnerability and impact analysis can therefore support SRAs and mitigation measures and enhance the response in the case of volcanic ash contaminated airspace. It is worth noting that there is still no agreement on critical ash concentration thresholds or any other method (retrievals, measurements, ingestion rate) that may be used to characterize critical conditions for aircraft. This poses a high limitation to the application of impact assessment methodologies such as the one presented here. Further work should support the definition of thresholds and fragility functions in order to increase reliability of results.

In this work, we have proposed several ways of estimating impacts on the air traffic system, and our results give a wide perspective of the spatial and temporal magnitude of impacts. According to Fig. 11, all eruptive scenarios produce impacts in the London area, but the Askja OES 1875-type and Katla LLERS scenarios can result in major impacts for the whole European air traffic system. Low-magnitude, short-duration activity such as a 2000-type Hekla ERS does not result in high impacts on central European air traffic, but can disrupt relevant connections for the national economies involved (i.e., Reykjavík–Copenhagen, London–Dublin). The probability of having hazardous mass concentrations for more than 12 h (Biass et al., 2014) shows that high-magnitude scenarios such as the 1875-type Askja OES event can cause major disruptions (> 1 % probability) to London air traffic. Also, lower-magnitude but long-lasting activity such as a Katla LLERS scenario has a > 1 and > 5 % probability of producing 12 h lasting disruption to London and Scotland, respectively, where the important airports of Glasgow and Edinburgh could be affected. Tables 6 and 7 show expected disruptions to Keflavík and London airports, based on averaged data. Note that this first-level impact assessment does not take into account the hour of the day and/or the day of the year in which a disruption occurs, which neglects differences between peak and off-peak (night and early morning) times. Average persistence times give information on the expected duration of disruptions, but given that the standard deviation for persistence time is on the order of 5–10 h (Biass et al., 2014), a high uncertainty is associated with these values. Nevertheless, this analysis allows for estimation on the order of magnitude of expected impacts and may support the definition of an "acceptable risk" based on averaged long-term values, which could eventually support a practical framework for risk management. Finally, average arrival time maps identify which airports and areas may need response plans and gives an idea of how much time is available for operations such as moving aircraft into hangars or part of the fleet to other airports. In fact, Guffanti et al. (2010) have shown how most damaging incidents during the last 60 years occurred within the first 1000 km from source volcanoes and within the first 24 h after eruption onset. The results of this impact assessment may therefore support the definition of strategies for many stakeholders involved in air traffic management during volcanic eruptions.

We also estimated impacts on FIRs (Fig. 11), accounting for the presence of ash at all FLs. The same impact analysis has been performed at specific FLs (Supplement Fig. S3), leading to significantly different results. In fact, impacts at a given FL strongly depend on the range of column heights of each eruption scenario, which in turn influences the probability of having ash at different FLs. For example, the Hekla ERS 2000-type scenario does not cause impacts at FL300 but only at lower levels. Consequently, a long-term impact assessment based on FL300 underestimates the expected impacts of low-magnitude eruptions such as the 2000- and 1947-type Hekla ERS scenarios. Analogously, impact assessment at airports (Tables 6 and 7) could be done considering all FLs or restricted at FL050, where most takeoff and landing operations take place. Given that air traffic management is based on the capacity of airspace sectors and these include several FLs (Cook, 2007), the second option seems more useful for decision making. For these reasons, we encourage the use of expected impact maps at FIRs, which are comprehensive of all FLs and provide a synthetic, conservative and meaningful support for the development of an SRA and other risk management plans.

Finally, this work has estimated the socioeconomic vulnerability of Europe to air traffic disruptions. The 2010 eruption of Eyjafjallajökull demonstrated that impacts at strategic airports such as London produce major systemic impacts on the rest of the European air traffic network and indirect socioeconomic impacts at a global scale (Oxford Economics, 2010). One example is the interruption of Kenyan exports to the UK (BBC News, 2010), which caused an economic impact on Kenyan agricultural sectors (Alexander, 2013). Here we did not describe such interactions but instead proposed a methodology to compare different sources of information that quantify the dependency of European areas on air traffic. The combination of demographic, trade and accessibility information (Supplement Fig. S3) identifies NUTS-2 regions with higher dependency on air traffic (Fig. 10), i.e., those more vulnerable to air traffic network disruptions. Moreover, the comparison of vulnerability maps for NUTS-2 regions and impact assessment results (Fig. 11 and Tables 6 and 7) identifies the most impacted areas from explosive eruptions in Iceland. For example, Ireland has a high vulnerability because it is an island (which inherently has a low multi-modal accessibility) and has strong social and commercial relationships with the UK, resulting in high socioeconomic impacts in the event of air traffic disruption. Also, Nordic countries such as Denmark and Norway are likely to be affected, in particular those regions with lower multi-modal accessibility. Flexibility of the transportation system and multi-modal accessibility are in fact critical factors that strongly influence the societal response to air traffic disruptions (Alexander, 2013). Moreover, a strategy that allows taking advantage of all different transportation means can strongly reduce losses during emergencies, as shown by Jones and Bolivar (2011) for the case study of Malta during the 2010 aviation disruption. Finally, civil aviation disruption is not only a problem for private stakeholders – it affects all of society, requiring procedures to mitigate the socioeconomic risk (Vainikka, 2010). Results of the vulnerability and impact assessment performed at the European level can support a socioeconomic impact analysis and the development of risk management plans. Data from European projects such as Eurostat, ESPON and TRACC are extremely relevant to support this analysis.

5.3 Caveats

First, the main aim of this work is identifying the areas that are expected to suffer impacts in the event of the selected scenarios occurring, at both the national and European scale. Given the difficulty in gathering specific data, our analysis does not account for physical vulnerability of most features. Thus, our simplified approach does not include an analysis of spatial inter- and intra-dependencies and cascading effects, as it relies on the characterization of physical vulnerability, which is beyond the scope of this work. The systemic aspects is covered only partially, by identifying specific elements and infrastructures that are important to the system performance on an a priori basis and assessing their expected impacts. This limitation is particularly important with regards to road and electricity network disruptions, whose failure may cause the disruption of dependent services and infrastructures and eventually lower the capacity of response of areas. Studies on electricity infrastructure vulnerability suggest that this analysis should start identifying where, how often, and for how long the electricity supply will be interrupted. This analysis should be performed by splitting the network at specific delivery points, implying a detailed knowledge of its structure (Kjølle et al., 2011). In order to be realistic and produce usable results, this kind of analysis requires therefore a collaboration between involved stakeholders (infrastructure holders, service providers and end users). The same conclusion can be drawn at the European scale, where interdependencies between elements are closely related to specific management plans of stakeholders involved (airlines, service providers). Thus, our work poses the basis for a specific analysis of these interdependencies by performing the first vulnerability and impact assessment for tephra fallout and dispersal in Iceland and Europe, and pointing out this issue to the stakeholders involved in territorial planning and long-term risk management. Second, the methodology proposed here is focused on a specific hazard caused by explosive volcanic eruptions (i.e., volcanic ash fallout and dispersal). But, given that there are other hazards at both scales that potentially affect the exposed targets, outcomes of our vulnerability and impact assessment could support multi-risk initiatives and be interfaced with specific analyses. For these reasons, we base our methodology on an integrated framework for vulnerability assessment proposed within the European project ENSURE (Menoni et al., 2012). At the European scale, this work may contribute to a multi-risk assessment including other hazards for aviation, such as volcanogenic SO_2 or mineral dust. At the national scale, volcanic eruptions are the hazardous phenomenon that poses the higher threat to societies by means of many hazardous phenomena such as lava flow and *jökulhaups* (glacial outburst floods). In particular, in 1996 and 2011, *jökulhaups* in southern Iceland destroyed parts of Route 1 (main Ring Road) and two bridges. It is worth noting that these events usually happen at the very local scale, while ash fallout and dispersal have a wider spatial range. For these events to be analyzed in a multi-risk framework, eruptive scenarios should be modified and/or complemented in order to include these events. Further work is therefore required in this field and may enhance the integration of our results in a multi-risk framework.

6 Conclusions

This work represents the first example of a strategy that can be applied to various volcanic settings for the multi-scale impact assessment for tephra dispersal and deposition. The outcomes of such a strategy are designed to support decision making at both the national and the European scale. In particular, impact maps could improve preparedness and help develop risk mitigation actions in Iceland and support long-term risk management plans of companies that operate in the European airspace (e.g., SRA). Based on our analysis of the economic system at the national level and of critical airports, FIRs and air traffic routes at the European scale, we can draw the following conclusions:

At the national scale:

- In the case of an 1875-type OES occurring at Askja, the electricity network has a 10 % probability of being impacted for 700 km. The occurrence of LLERS at Katla and a 1947-type ERS at Hekla have a 10 % probability of impacting more than 250 km of the national electricity network. Finally, the occurrence of a 2010-type LLOES at Eyjafjallajökull has a 10 % probability of disrupting 122 km of the electricity network.
- In the case of a 1947-type ERS occurring at Hekla, five power plants have a 10 % probability of being affected by ash fallout. If selected scenarios at Askja or Katla were to happen, four power plants would have a 10 % probability of being affected by ash fallout, while other eruptive scenarios (2000 type at Hekla and 2010 type at Eyjafjallajökull have a low, but not null, probability of having impacts on power plants.
- In the case of any of the selected eruptive scenarios occurring, 1–10 km^2 of Icelandic croplands have a 10 % probability of being affected by ash fallout. Occurrence of eruptive scenarios at Askja and Katla have a 10 % probability of affecting 287 and 125 km^2 of pasture lands, respectively.

At the European scale:

- The occurrence of a 2000-type ERS at Hekla is likely to have very high impacts on the Reykjavík FIR (950 passengers stranded for at least 5 h) and high impacts for the London FIR (∼ 23 000 passengers stranded for at least 3 h).
- The occurrence of a 1947-type ERS at Hekla is likely to have very high impacts on the Reykjavík FIR (∼ 1500 passengers stranded for at least 8 h) and high impacts for the London FIR (∼ 27 000 passengers stranded for at least 4 h). The FIR of Paris, Brest and Marseille would also be strongly impacted.
- The occurrence of an 1875-type OES at Askja is likely to have very high impacts on the Reykjavík FIR (∼ 3600 passengers stranded for at least 18 h) and high impacts for the London FIR (∼ 60 000 passengers stranded for at least 8 h). FIRs above France, Germany and Scandinavia would also be impacted.
- The occurrence of an LLERS scenario at Katla is likely to have a very high impact on the Reykjavík FIR (∼ 4300 passengers stranded for at least 21 h) and

high impact for the London FIR ($\sim$ 78 000 passengers stranded for at least 10 h). It is also likely that FIRs above France, Germany and Scandinavia would be strongly impacted.

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ATTENTION¡

Pages 197 to 210 of the thesis are available at the editor’s web

Paper IV

A GIS-based tool to support air traffic management during explosive volcanic eruptions

C. Scaini, A. Folch, T. Bolić, L. Castelli

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Appendix B

Other publications produced during the PhD research

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Hazard assessment of far-range volcanic ash dispersal from a violent Strombolian eruption at Somma-Vesuvius volcano, Naples, Italy: implications on civil aviation.

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A multi-scale risk assessment for tephra fallout and airborne concentration from multiple Icelandic volcanoes - Part II: Hazard assessment

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A multi-scale risk assessment for tephra fallout and airborne concentration from multiple Icelandic volcanoes – Part 1: Hazard assessment

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Abstract. In order to assist the elaboration of proactive measures for the management of future volcanic eruptions in Iceland, we developed a new scenario-based approach to assess the hazard associated with tephra dispersal and sedimentation at various scales and for multiple sources. The target volcanoes are Hekla, Katla, Eyjafjallajökull and Askja, selected either for their high probabilities of eruption and/or their high potential impact. By coupling tephrostratigraphic studies, probabilistic techniques and modelling, we developed comprehensive eruption scenarios for both short- and long-lasting eruptions and compiled hazard maps for tephra ground deposition at a national scale and air concentration at a European scale using the TEPHRA2 and FALL3D models, respectively. New algorithms for the identification of realistic sets of eruptive source parameters are investigated, which assist the generation of probability density functions of eruption source parameters for the selected scenarios. Aggregation processes were accounted for using various empirical models. Outcomes, i.e. probabilities conditioned to the occurrence of an eruption, help the assessment and comparison of hazard levels at different scales. For example, at a national scale Askja has a 5–10 % probability of blanketing the easternmost half of the country with a tephra accumulation of at least 1 $\mathrm{kg\,m^{-2}}$. At a continental scale, Katla has a 5–10 % probability of producing ash clouds with concentrations of 2 $\mathrm{mg\,m^{-3}}$ over the UK, Scandinavia and northern Europe with a mean arrival time of 48–72 h and a mean persistence time of 6–18 h. In a companion paper, Scaini et al. (2014) present a vulnerability assessment for Iceland to ground deposition of tephra and for the European air traffic to airborne ash which, combined with the outcomes of the present paper, constitute one of the first comprehensive multi-scale risk assessment associated with tephra dispersal and sedimentation.

1 Introduction

Evaluation of the tephra hazard is necessary to carry out comprehensive risk assessments of explosive volcanoes. The process is commonly divided into a succession of logical steps, including the identification and the characterization of eruptive deposits in the field, the development of comprehensive eruptive scenarios based on field observations and the use of models to quantify the hazard related to each eruptive scenario (e.g. Biass and Bonadonna, 2013; Biass et al., 2013; Bonadonna, 2006; Bonasia et al., 2011; Cioni et al., 2003; Connor et al., 2001; Costa et al., 2009, 2012; Jenkins et al., 2012a; Leadbetter and Hort, 2011; Macedonio et al., 2008; Scaini et al., 2012; Volentik et al., 2009).

Although the hazard related to tephra dispersal and fallout rarely constitutes a direct threat to human lives, tephra can deposit on the ground up to hundreds of km away from the source and be dispersed thousands of km in the atmosphere. As a result, the impact from tephra varies with distance from the vent, resulting in complex vulnerability patterns of exposed elements (Blong, 1984; Connor et al., 2001). On the ground, tephra fallout can affect aspects such as human

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health, buildings, lifelines, economy or the environment. In the atmosphere, the residence time of ash can be as long as weeks, thus able to paralyse air traffic far away from the source, as demonstrated by the 2010 Eyjafjallajökull and the 2011 Puyehue–Cordón Caulle eruptions (Budd et al., 2013; Davies et al., 2010; Swindles et al., 2011; Wilkinson et al., 2012). Nonetheless, probabilistic studies of tephra dispersal tend to focus either on local ground deposition (e.g. Biass and Bonadonna, 2013) or on far-ranging atmospheric concentrations (e.g. Sulpizio et al., 2012), and only a few recent studies account for comprehensive multi-scale assessments (e.g. Scaini et al., 2012).

One crucial parameter for the description of the dispersal of tephra is the total grain-size distribution (TGSD). Centimetric to millimetric particles are controlled by gravitational settling and sediment in proximal to medial distances from the eruptive vent, whereas micrometric to submicrometric particles, when not aggregated, are controlled by larger-scale atmospheric processes and transported at continental scales (Folch, 2012). Depending on the assumptions used to model these two end-members, several modelling approaches have been developed to solve the advection–diffusion equation with analytical, semi-analytical or numerical strategies (Bonadonna et al., 2012; Folch, 2012).

Eruption scenarios are usually developed for a single volcano and are constrained by the availability of past data and the completeness of the eruptive record (Marzocchi et al., 2004). Through time, the definition of eruption scenarios has evolved from a "worst-case scenario" approach towards an evaluation of the entire possible range of activity at a given volcano. For example, early hazard maps for Cotopaxi volcano (Hall and Hillebrandt, 1988; Vink, 1984) are based upon isopach maps of two major eruptions with opposite wind directions in agreement with the regional wind patterns and the most important exposed human settlements. More recent studies considered a probabilistic approach and developed a set of eruptive scenarios of various intensities based on accurate stratigraphic studies (Biass and Bonadonna, 2011, 2013). Probabilistic techniques such as Monte Carlo simulations (e.g. Hurst and Smith, 2004) are nowadays an integral part of any hazard assessment for tephra dispersal and are used to investigate both the missing or inaccessible parts of the geological record and the impact of eruptions in a representative set of atmospheric conditions (Bonadonna, 2006).

For probabilistic modelling, the identification of eruption scenarios typically requires the definition of a probability density function (PDF) for each input parameter needed by a given model in order to account for the variability of eruptive processes (i.e. aleatoric uncertainty). For tephra fallout, several approaches have been used to define eruption scenarios, based on individual eruptions (Bonasia et al., 2011; Capra et al., 2008), eruptive styles (Macedonio et al., 2008), intensities/magnitudes (Scaini et al., 2012; Yu et al., 2013) or VEI classes (Biass and Bonadonna, 2013), mostly applied to a single source. However, some regions in the world are

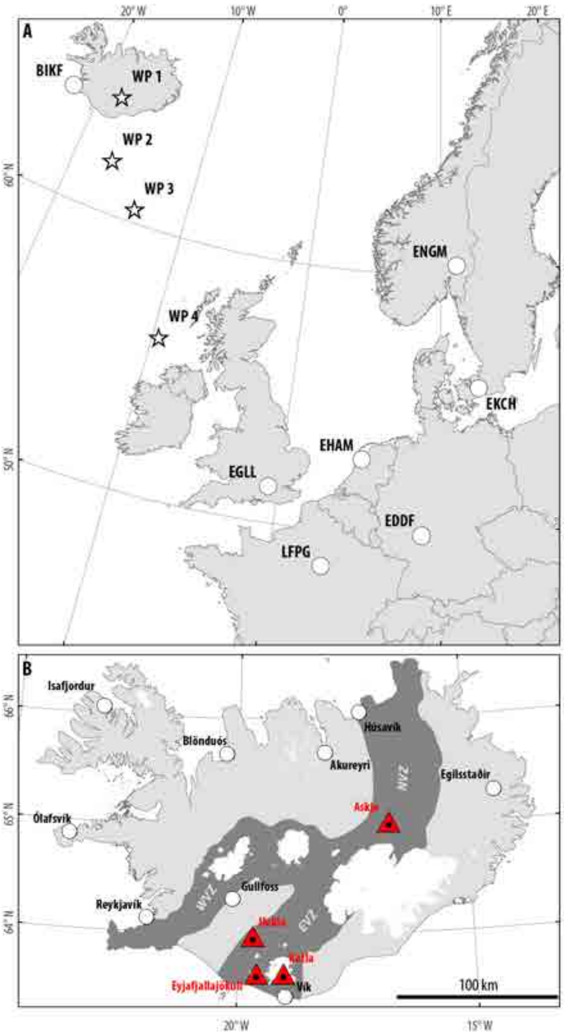

Figure 1. Overview of the computational domains at **(a)** large and **(b)** small scales: **(a)** shows the locations of wind profiles (stars) used in Fig. 3 and the main airports (circles) of London Heathrow (EGLL), Paris Charles de Gaulle (LFPG), Amsterdam Schiphol (EHAM), Frankfurt (EDDF), Oslo Gardermoen (ENGM), Copenhagen Kastrup (EKCH) and Keflavik (BIKF); **(b)** shows the target volcanoes (red triangles) and the relevant volcanic zones for this study (WVZ: Western Volcanic Zone; EVZ: Eastern Volcanic Zone; NVZ: Northern Volcanic Zone).

under the threat of more than one volcano, sometimes presenting a wide range of known eruptive styles and characteristics, and the development of comparable eruption scenarios for a set of volcanoes becomes an obvious necessity (e.g. Ewert, 2007; Jenkins et al., 2012a, b; Lirer et al., 2010; Simkin and Siebert, 1994).

Here, we present a medium- to long-term multi-scale scenario-based hazard assessment for ground tephra accumulation and far-range atmospheric ash dispersal from four

Icelandic volcanoes – Hekla, Katla, Askja and Eyjafjallajökull – selected either for their high probabilities of eruption in the near future or their high potential impact (Fig. 1). Due to the different eruptive styles and the varying degree of knowledge of the eruptive history at these volcanoes, we developed consistent probabilistic eruption scenarios based on field data, literature studies and historical reports. The tephra-related hazard was assessed for each eruption scenario at a local scale (i.e. ground tephra accumulation) with the analytical model TEPHRA2 (Bonadonna et al., 2005) and at a regional scale (i.e. atmospheric concentration) with the numerical model FALL3D (Costa et al., 2006; Folch et al., 2009). A population of 10 years of wind obtained from reanalysis data sets was used to assess statistical atmospheric conditions. Outputs include (i) probabilistic maps of ground tephra accumulation and atmospheric concentration for relevant thresholds, (ii) mean atmospheric arrival time and persistence time, (iii) probability maps of atmospheric arrival time and persistence time for relevant thresholds, and (iv) ground hazard curves for critical facilities in Iceland. In a companion paper, Scaini et al. (2014) present a vulnerability assessment for both Iceland and the European air traffic system and use the outcomes of this study to perform a multi-scale impact analysis. This comprehensive assessment is intended to act as a first step towards the elaboration of pro-active measures for the management of explosive volcanic crisis.

Table 1. Historical eruptions at the central volcano of Hekla (see Thordarson and Larsen, 2007, and references therein). Tephra volumes are recorded as "freshly fallen" (i.e. 40 % larger than volumes of old eruptions inferred from field mapping; Thorarinsson, 1967). Following the typical pattern of mixed eruptions at Hekla, plume heights correspond to the maximum altitude reached a few minutes after the onset of the eruption. NA: not available.

Eruption year	Tephra (km^3)	Max plume height (km a.s.l.)	Preceding interval (years)
2000	0.01	12	9
1991	0.02	11.5	10
1980–1981	0.06	15	10
1970	0.07	16	22
1947–1948	0.18	32	101
1845	0.23	NA	77
1766–1768	0.4	NA	73
1693	0.3	NA	56
1636	0.18	NA	39
1597	0.29	NA	86
1510	0.32	NA	120
1389	0.15	NA	47
1341	0.18	NA	40
1300	0.5	NA	78
1222	0.04	NA	15
1206	0.4	NA	46
1158	0.33	NA	53
1104	2	36	> 230

2 Geological setting

Iceland is the result of the combined effects of a spreading plate boundary and a mantle plume (Allen et al., 1999; Vink, 1984; White et al., 1995; Wolfe et al., 1997). Current active volcanic zones (i.e. the neovolcanic zones) are the superficial expression of the mid-oceanic ridge. Arranged as discrete 15–50 km wide belts of active faulting and volcanism, they collectively cover a total area of 30 000 km^2 (Gudmundsson, 2000; Thordarson and Höskuldsson, 2008; Thordarson and Larsen, 2007). Volcanic zones host volcanic systems which, in their simplest forms, contain either a fissure swarm, a central volcano or both (Gudmundsson, 1995a, b). When present, the central volcano is the focal point of eruptive activity and the largest edifice in each system under which crustal magma chambers can develop, giving rise to either silicic or basaltic magmatism. In contrast, only basaltic magmas are erupted within fissure swarms (Larsen and Eirìksson, 2008; Thordarson and Larsen, 2007).

2.1 Target volcanoes

In this paper, we focus on eruptions occurring at the central volcanoes of four different volcanic systems located within two different volcanic zones: the Eastern Volcanic Zone (EVZ) and the Northern Volcanic Zone (NVZ; Fig. 1), ranked first and third in terms of volcanic activity in Iceland throughout the Holocene (Thordarson and Höskuldsson, 2008). No volcanic system was considered within the second most active volcanic zone, the Western Volcanic Zone (WVZ), because the EVZ is an active axial rift propagating southwards, thus taking over the activity of the WVZ (Mattsson and Höskuldsson, 2003; Thordarson and Larsen, 2007). The EVZ is divided into two sectors. In the north, the axial rift zone is characterized by a thick crust, high heat flow, well-developed tensional features and the production of tholeitic basalts. The southern propagating tip of the EVZ is often referred to as a flank zone, which lies on an older and thinner crust presenting a lower heat flow. Here, tensional features are poorly developed and the magma production consists mainly of transitional alkali to alkali basalts (Loughlin, 2002; Mattsson and Höskuldsson, 2003). We consider three volcanoes from the EVZ (Hekla, Katla, and Eyjafjallajökull; Fig. 1) and one from the NVZ (Askja).

Amongst the selected volcanoes and in terms of activity since the settlement during the last 1100 years, Hekla is the most active with 18 eruptions from the central vent followed by Katla (18 eruptions), Eyjafjallajökull (3 post–17th century eruptions) and Askja (1 central vent eruption). Tables 1 and 2 summarize the recent eruptions of Hekla and Katla, respectively. The Supplement comprises a detailed description of

Table 2. Historical eruptions at Katla that produced tephra volumes $> 0.1\,km^3$ (Thordarson and Larsen, 2007). Uncompacted volumes are presented either as moderate (> 0.1–$0.5\,km^3$) or large ($> 0.5\,km^3$).

Eruption year	Tephra volume
1918	Large
1755	Large
1721	Moderate
1660	Moderate
1625	Large
1500	Large
1416	Moderate
1357	Moderate
1262	Large
920	Moderate

the typical activity of these four volcanoes. The most striking features will be reviewed in Sect. 4.1. together with the eruption scenarios.

3 Method

We aim to assess the hazard caused by the ground deposition and the atmospheric dispersion of tephra. Probabilistic approaches are adopted in order to account for the variability (i.e. aleatoric uncertainty) related to both eruptive and atmospheric conditions. We quantify the probability of hazardous mass load on the ground:

$$P\left[M(x,y) \geq M_\mathrm{T} |\,\mathrm{eruption}\right], \tag{1}$$

where $M(x,y)$ is the tephra mass load ($\mathrm{kg\,m^{-2}}$) accumulated at a given location and M_T a mass load threshold (e.g. Bonadonna, 2006). For a given eruption scenario, the probability P_M at a pixel (x,y) is quantified by counting the number of times a given threshold of load is reached over the total number of runs N:

$$P_\mathrm{M}(x,y) = \frac{\sum_{i=1}^{N} n_i}{N}, \tag{2}$$

where

$$n_i(x,y) = \begin{cases} 1 & \text{if } M_i(x,y) \geq M_\mathrm{T} |\,\mathrm{eruption} \\ 0 & \text{otherwise.} \end{cases} \tag{3}$$

For atmospheric concentrations, we start by quantifying

$$P\left[C(x,y,z,t) \geq C_\mathrm{T} |\,\mathrm{eruption}\right], \tag{4}$$

where $C(x,y,z,t)$ is the tephra mass concentration in the atmosphere ($\mathrm{mg\,m^{-3}}$) at a given point and time instant and C_T a mass concentration threshold. For a given eruption scenario, the probability of disruption P_C at a point (x,y,z) is quantified by counting the number of times a given mass concentration threshold is exceeded over the total number of runs N:

$$P_\mathrm{C}(x,y,z) = \frac{\sum_{i=1}^{N} n_i}{N}, \tag{5}$$

where

$$n_i(x,y,z) = \begin{cases} 1 & \text{if } C_i(x,y,z) \geq C_\mathrm{T} |\,\mathrm{eruption} \\ 0 & \text{otherwise.} \end{cases} \tag{6}$$

Disruption can be calculated at a given height or flight level (FL) or be comprehensive of all FLs, that is, considering that disruption occurs at a point (x,y) if the critical condition is achieved at any height z above the point. Note that for a given run, disruption occurs regardless of the number of model time steps during which Eq. (6) is verified. In order to provide a comprehensive picture of interest for air traffic management (ATM), we also quantify persistence and the first arrival time of a concentration threshold C_T. The persistence is calculated by counting, for each run, the time interval in which the critical concentration threshold C_T is exceeded at a pixel (x,y,z). The first arrival time (hereafter referred to as *arrival time*) computes the time from the beginning of the eruption to the first detection of the concentration C_T at a pixel (x,y,z). Both persistence and arrival time were quantified as mean (i.e. average value at a pixel (x,y,z) over the entire number of runs), as standard deviation and as the probabilities of exceeding relevant thresholds of persistence and arrival times following the same approach as Eq. (5) at both specific FL and considering all vertical levels simultaneously.

In this section, we review (i) the models used at different scales, (ii) the probabilistic strategies adopted in this study, and (iii) the strategy used to account for particle aggregation processes.

3.1 Tephra dispersal modelling

3.1.1 Ground accumulation

The hazard related to ground deposition of tephra was assessed at the scale of Iceland using the steady semi-analytical advection–diffusion model TEPHRA2 (Bonadonna et al., 2005) following the approach detailed in Biass and Bonadonna (2013). TEPHRA2 requires five main input parameters: plume height, eruption duration, erupted mass, TGSD and particle density. It also requires a vertical wind profile, a calculation grid and three empirical parameters: a fall-time threshold acting as a threshold for the modelling of the diffusion of small and large particles (i.e. power law vs. linear diffusions), a diffusion coefficient used for the linear diffusion law and an apparent eddy diffusivity fixed at $0.04\,\mathrm{m^2\,s^{-1}}$ for the power law diffusion (Bonadonna et al., 2005; Suzuki, 1983; Volentik et al., 2009). Empirical parameters can be estimated either using TEPHRA2 in inversion mode when enough field data are available (Connor and

Connor, 2006; Volentik et al., 2009) or using analogue eruptions. Wind conditions for the 2001–2010 period were extracted from the ECMWF Era-Interim Reanalysis data set at a 1.5° resolution. The calculation grid covers the small computational domain (Fig. 1) at a resolution of 1 km. When needed, smaller calculation grids were used at a resolution of 500 m.

3.1.2 Atmospheric concentration

The hazard related to ash dispersal was assessed at the continental scale using the non-steady numerical advection–diffusion–sedimentation model FALL3D coupled with probabilistic strategies (Costa et al., 2006; Folch et al., 2009; Folch and Sulpizio, 2010; Scaini et al., 2012; Sulpizio et al., 2012). Eruption source parameters (ESPs) required by FALL3D include plume height, mass eruption rate (MER), eruption date and eruption duration.

All simulations compute 168 h of dispersal on a 120×60 grid with a horizontal resolution of approximately 0.5 degrees. Vertical layers are defined from 0 to 36 000 m with a variable vertical interval. The mass distribution follows Suzuki (1983) and Pfeiffer et al. (2005), with $A = 4$ and $\lambda = 5$. Such values were chosen since (i) all eruptions are of subplinian/Plinian types and (ii) only the fine fraction is modelled with FALL3D to assess the far-range dispersal. The terminal velocity is given by Ganser (1993), with a sphericity fixed to 0.9. The vertical diffusion coefficient was fixed to $10\,\mathrm{m^2\,s^{-1}}$ and the horizontal diffusion coefficient was calculated using the CMAQ model parameterization (Folch et al., 2009). Meteorological fields for the considered period were extracted from the ECMWF Era-Interim Reanalysis at 1.5° every 3 h, covering northern and central Europe (Fig. 1). Outputs are produced at a regular 5000 ft vertical interval from FLs 050–400.

3.2 Probabilistic strategies

Several approaches exist to assess the probability distribution of reaching a hazardous accumulation of tephra given an eruption (Bonadonna, 2006). In order to account for variable parameters (i.e. eruptive and atmospheric conditions), a large number of model runs are performed varying input parameters, including eruption date (i.e. wind profile for TEPHRA or 4-D variables for FALL3D). Each run consists either of a single occurrence of the model (i.e. short-lasting eruptions) or a set of simulations in time (i.e. long-lasting eruptions). When an approach with variable eruptive parameters is adopted, a PDF must be defined to constrain the stochastic sampling. The definition of the PDF, which reflects the knowledge of the system, is relevant to the definition of eruptive scenarios and will be tackled later.

3.2.1 Short-lasting eruptions

One eruption scenario (OES)

The OES is an approach used to compile the probability of reaching a given threshold of tephra accumulation in variable wind conditions, with ESP chosen deterministically. Figure 2a summarizes the algorithm applied to short-lasting eruptions (Bonadonna, 2006). First, the plume height, the eruption duration, the total mass and the TGSD are fixed deterministically. Then, for each single run of the model, an eruption date is sampled from which the corresponding wind conditions are extracted from the meteorological database.

Eruption range scenario (ERS)

The ERS approach allows for a stochastic sampling of ESP at each run as well as wind conditions, where each variable parameter is characterized by a range and a PDF (Bonadonna, 2006). Figure 2b shows the algorithm used for the ERS. First, a plume height, an eruption duration and an eruption date are sampled from their respective PDF, and a maximum total mass for the eruption scenario is set. From the eruption date, the respective meteorological conditions are loaded, which, combined with the plume height, allows for the calculation of the MER using the method of Degruyter and Bonadonna (2012). A test is then performed to assess whether the resulting mass, calculated by combining the MER and the eruption duration, fits into the initial assumptions of mass range. If the test is negative, all parameters are resampled, otherwise the selected input parameters are sent to the model.

3.2.2 Long-lasting eruptions

New eruption scenarios were developed to assess the hazard related to long-lasting eruptions (Fig. 2c and d). For long-lasting eruptions, ESPs are expressed as time series at constant time intervals, Δt, defined depending upon the availability of data (i.e. measurements of plume height, wind profiles). The application of algorithms shown in Fig. 2c and d varies depending on the scale of the hazard assessment, and thus the model used. When used with steady models (e.g. TEPHRA2), they consist of discrete model runs at constant time intervals, and the final hazard maps are the sum of all individual runs (e.g. Scollo et al., 2013). When used with non-steady models (e.g. FALL3D), ESPs are updated at a constant time interval. For clarity, we will refer to any single run or update of the model as “occurrence”, i.e. for long-lasting eruptions, a run (i loop in Fig. 2) consists of several occurrences (j loop in Fig. 2).

Long-lasting one eruption scenario (LLOES)

The LLOES relies on the same concept as the OES, i.e. eruptive parameters chosen deterministically with varying wind

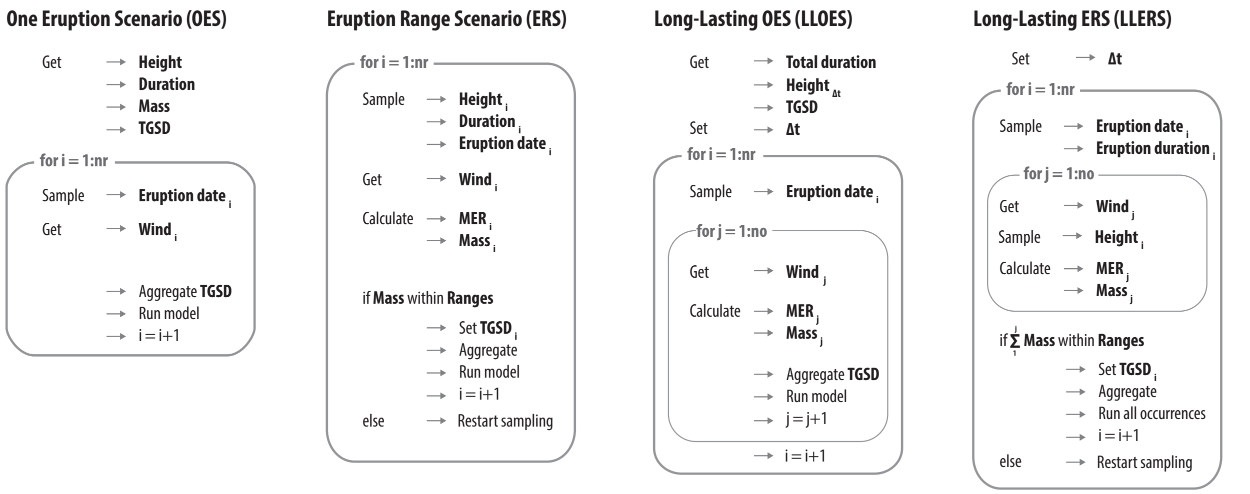

Figure 2. Algorithms applied for the different eruption scenarios used in this study. *Get* refers to access to deterministic data, *Set* defines a variable and *Sample* indicates a stochastic sampling.

conditions, only applied to long-lasting eruptions. Here, the total eruption duration, the time series of plume heights and the TGSD are set deterministically, and the time interval (Δt) is set based on the availability of data. At each run of the model, an eruption date is sampled and the corresponding wind conditions are extracted based on the eruption duration and Δt. At each occurrence, knowing Δt, the plume height and the wind conditions at the given time, the MER and the mass are calculated averaged over the interval length, and a new occurrence of the model is performed. Each run is the sum of all occurrences performed.

Long-lasting eruption range scenario (LLERS)

The LLERS applies the ERS strategy to long-lasting eruptions. Eruptive parameters are stochastically sampled as time series at a constant Δt. Following the algorithm in Fig. 2d, a mass boundary is first set. At each run, an eruption date and an eruption duration are sampled. At each occurrence, a plume height is sampled from a PDF, and the MER is calculated based on the wind conditions for that specific date using the method of Degruyter and Bonadonna (2012). If the sum of the mass of all occurrences of a single run falls out of the initial mass assumptions, the sampling process is restarted. If not, input values for all occurrences are sent to the model. Eventually, each run is the sum of all occurrences performed.

3.3 Ash aggregation

Aggregation processes are known to modify deposition trends along the dispersal axis by aggregating fine particles (typically $< 100\,\mu$m) into larger clusters (Brown et al., 2012; Rose and Durant, 2011). The aggregation of fine particles into larger aggregates results in premature sedimentation in the proximal area and in a relative depletion of fines away from the vent (Carey and Sigurdsson, 1982; Hildreth and Drake, 1992), possibly leading to an underestimation of the hazard in proximal areas and an overestimation in distal sectors. The fallout of aggregates has been characterized during numerous eruptions, including the 1980 eruption of Mount St. Helens (Carey and Sigurdsson, 1982; Durant et al., 2009), the ongoing eruption of Montserrat (Bonadonna et al., 2002) and the 2010 eruption of Eyjafjallajökull (Bonadonna et al., 2011; Taddeucci et al., 2011). Although aggregation is a topic of intense research, no satisfactory parameterization of this process has been achieved yet (e.g. Brown et al., 2012; Costa et al., 2010; Folch et al., 2010; Van Eaton and Wilson, 2013; Van Eaton et al., 2012).

Several models attempt to describe aggregation processes using either empirical (Bonadonna and Phillips, 2003; Carey and Sigurdsson, 1982; Cornell et al., 1983) or numerical approaches (Costa et al., 2010; Folch et al., 2010). Here, we use the empirical approach of Bonadonna et al. (2002) and observations of Bonadonna et al. (2011) to modify the TGSD before running the models. Following this strategy, we remove an equal proportion of masses of fine particles from phi classes $\geq 4\Phi$, which are equally redistributed between classes -1Φ and 3Φ. The amount of fine particles removed, i.e. the aggregation coefficient, is stochastically sampled between 20 and 80 % on a uniform distribution at every loop increment on the algorithms shown in Fig. 2. The choice of such a range is based on field observations presented in Bonadonna et al. (2002, 2011).

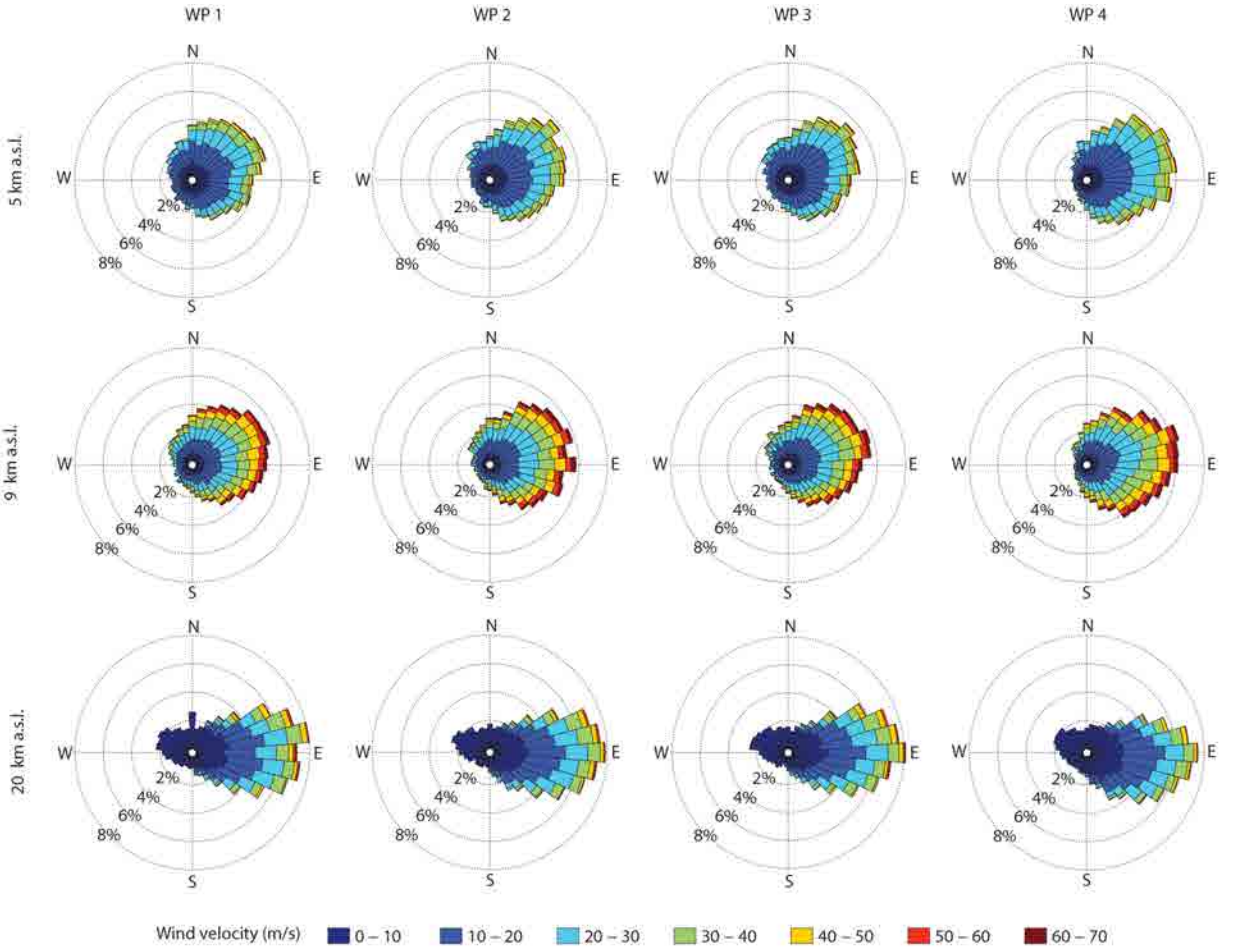

Figure 3. Wind analysis at three atmospheric levels along a N–S section from Reykjavík to the UK (Fig. 1) from the ERA-Interim Reanalysis database. These wind roses show the probability that the wind will blow in given directions and speed intervals.

4 Results

4.1 Identification of eruption scenarios

The identification of eruption scenarios is based upon the eruption history presented in the Supplement for each volcano. Here, only the historical catalogue of eruptions was used for three reasons. Firstly, with a mean eruption of > 20 events per century (Thordarson and Höskuldsson, 2008), reports and eye-witness accounts since human settlement constitute a valuable source of information when developing eruption scenarios. Trying to merge such a data set with an eruption catalogue based on stratigraphic studies only results in discrepancies in the completeness of the eruptive record, making any comparison difficult. Secondly, the climate of Iceland is prone to fast erosion of freshly fallen deposits, inducing a bias towards large eruptions when trying to assess the prehistoric eruptive activity. Thirdly, since it is recognized that mean eruption frequencies are strongly correlated to glacier load (Albino et al., 2010), any attempt to assess eruptive patterns during older time periods might not be representative of the actual climate and load. As a result, the hazard assessment presented here implies that a future eruption at any of the four volcanoes will follow behaviours similar to the eruptive style displayed in historical times.

Additionally, we only focus on the activity occurring at the central vent of the selected volcanic systems as no explosive eruptions occurred from fissure swarms. Both ground accumulation and atmospheric dispersal were tackled probabilistically, using the models TEPHRA2 and FALL3D, respectively. Since statistical analysis shows neither monthly nor seasonal trends, we used a population of 10 years of wind data (2001–2010). Figure 3 shows wind roses at three altitude levels for points specified in Fig. 1.

4.1.1 Hekla

Out of all volcanoes considered in this study, Hekla presents the most accurate historic record with 18 identified and reasonably well-described eruptions, a good characterization of 5 of them and a TGSD of the 2000 eruption (Gronvold et al., 1983; Gudmundsson et al., 1992; Höskuldsson et al., 2007; Thorarinsson, 1967; Thorarinsson and Sigvaldason, 1972). From the 18 eruptions presented in Table 1, we discarded the eruption of 1104 from the eruptive record as it belongs to the larger magnitude and lower frequency H1–5 series and occurred after a repose interval of >230 years, more than twice the maximum repose time in historical times (Larsen and Eirìksson, 2008; Thordarson and Höskuldsson, 2008; Thordarson and Larsen, 2007). Since a large majority of the tephra is produced during the opening phase of "mixed" eruptions (Supplement), we only model the first part of the eruption.

Based on the historical period summarized in Table 1, two eruption scenarios were identified for Hekla and named after the best-described eruption of each cluster. First, a 2000-type eruption was identified to describe eruptions that have occurred at a ~10-year frequency. This eruption scenario considers all available data for the eruptions of 1222, 1970, 1981, 1991 and 2000. Second, a 1947-type eruption is considered representative of large Plinian eruptions occurring on an average of one per century starting from the eruption of 1158 (Thorarinsson, 1967).

2000-type scenario

The good knowledge of eruptions considered in the 2000-type scenario allows for the identification of well-constrained ranges of ESP for plume heights and erupted masses, and, subsequently, the use of the ERS strategies. Table 3 and Fig. 4 summarize ranges of ESPs and their corresponding PDFs. In agreement with historical witnesses, the duration of the intense opening phase was fixed between 0.5 and 1 h and sampled on a uniform PDF. Based on Table 1 and following the algorithm presented in Fig. 2, a mass constraint was fixed between 6.9×10^9 and 6.9×10^{10} kg considering a deposit density of 691 kg m^{-3}. Based on observations, plume heights were defined between 6 and 16 km a.s.l. and sampled on a logarithmic scale in order to slightly favour small events over large ones.

The TGSD for the 2000 eruption shows bimodality with peaks at -3Φ and 3Φ (Fig. 4c) and a minimum at 1Φ. This TGSD was used as representative for the 2000-type eruption scenario and was varied at each run. First, considering 1Φ as a boundary between the two populations, we varied the relative weight percentage of the two populations between 30 and 70 %. Second, we applied the aggregation model described in Sect. 3.3 on the resulting modified TGSD by removing between 20 and 80 % of fines. Figure 4c shows the three states of the TGSD for one of the 1000 runs.

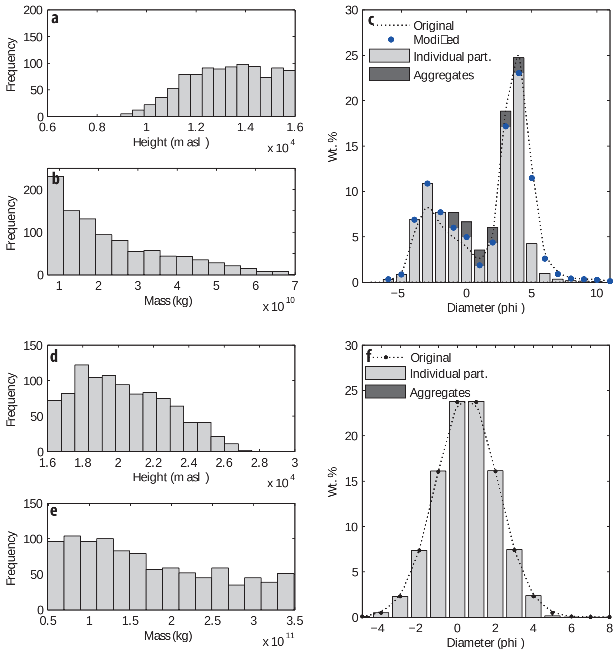

Figure 4. ESP used for **(a–c)** the Hekla 2000-type and **(d–f)** the Hekla 1947-type scenarios (see Table 3 for details). **(a)** and **(d)**: plume height (m a.s.l.); **(b)** and **(d)**: erupted mass; **(c)** and **(f)**: total grain-size distribution. Histograms in **(c)** and **(f)** show both the fractions of individual particles (light grey) and aggregates (dark grey) generated based on the algorithm explained in the text; *original* indicates the original grain-size distribution obtained from sieving (i.e. not containing any aggregates).

1947-type scenario

A similar approach was applied to the 1947-type scenario. Since only sparse estimates of plume heights are reported in the literature for this eruption type, the sampling was constrained between 16 (i.e. the highest boundary of the 2000-type eruption) and 30 km a.s.l. on a logarithmic PDF (Fig. 4d). Based on Table 1, the mass constraint was defined between 6.9×10^{10} and 3.5×10^{11} kg (Fig. 4e). The resulting distribution of plume heights is shown in Fig. 4d and displays a maximum of sampling around 18–20 km a.s.l. No solution compatible with the mass constraint was found for plumes higher than 27 km. Figure 4e shows a rather uniform mass distribution, though slightly biased towards lower values.

Since no sufficient measurements exist to infer the TGSD for any of these eruptions, we consider here a Gaussian distribution ranging from -5 to 8Φ. We allowed a variability of Md_Φ and σ_Φ on uniform PDF between -1Φ to 1Φ and 1Φ to 2Φ, respectively. The aggregation model was applied, with aggregation coefficients varying between 20 and 80 % for all bins $\geq 4\Phi$.

Table 3. Summary of ESP for all eruption scenarios.

Volcano	Reference eruption	Modelling strategy	Plume height (km a.s.l.)	Duration	Mass	Md Φ	σ Φ	Max Φ	Min Φ	Aggregation
Hekla	2000	ERS	6–16[a]	0.5–1 h[b]	6.9×10^9–6.9×10^{10}	–	–	−6	11	0.2–0.8[b]
	1947	ERS	16–30[a]	0.5–1 h[b]	6.9×10^{10}–3.5×10^{11}	−1–1[c]	1–2[c]	−5	8	0.2–0.8[b]
Katla	Historical moderate/large[d]	LLERS	10–25[a]	1–4 days[b]	7×10^{11}–7×10^{12}	−1–1[c]	1–2[c]	−7	8	0.2–0.8[b]
Eyjafjallajökull	2010	LLOES	2.5–7.8[e]	40 days	–	–	–	−2	11	–
Askja	Askja C	OES	23	1 h	4.8×10^{11}	–	–	−6	6	0.2–0.8
	Askja D	OES	26	1.5 h	5.0×10^{11}	–	–	−10	6	0.2–0.8

[a] Logarithmic; [b] Uniform; [c] Gaussian; [d] Thordarson and Larsen (2007); [e] IMO (Arason et al., 2011)

Table 4. Critical thresholds for probability calculation.

Threshold	Unit	Potential impact	References
Ground load			
1	kg m^{-2}	Fluorine poisoning, electric flashover, closing of airports	Bebbington et al. (2008), Blong (1984), Thorarinsson and Sigvaldason (1972), Wilson et al. (2011)
10	kg m^{-2}	Impact on road traffic, damages on crops	Blong (1984), Wilson et al. (2011)
100	kg m^{-2}	Structural damages of weakest structures	Blong (1984), Marti et al. (2008), Spence et al. (2005)
Atmospheric concentration			
2	mg m^{-3}	EUR/NAT low/medium ash contamination boundary	ICAO (2010)
Arrival time			
24	h	–	Guffanti et al. (2010)
Persistence time			
12	h	–	Ulfarsson and Unger (2011)

4.1.2 Katla

Numerous eruptions from Katla have been well described and documented, but only a few quantitative constraints exist. Based on Table 2 and Larsen (2010), about 10 historical eruptions produced tephra volumes $> 0.1\,\mathrm{km}^3$, with only the 934–940 Eldgjá eruption responsible for a volume $> 1\,\mathrm{km}^3$. Since the Eldgjá eruption originated from the surrounding fissure swarm rather than the central volcano, we discard it from the eruption record used in this study, resulting in relevant tephra volumes ranging from 0.1 to $1\,\mathrm{km}^3$. Historical eruptions at Katla are known to have lasted from 2 weeks to 5 months, with most of the tephra produced during the first days. No silicic eruptions were witnessed during historical times, with the last SILK layer erupted 1675 years BP (Larsen et al., 2001).

As a result, a LLERS strategy was applied to Katla volcano in order to assess the hazard related to a future moderate to large basaltic eruption (Table 2). According to the existing literature, plume heights were sampled between 10 and 25 km a.s.l. on a logarithmic PDF (Einarson et al., 1980; Larsen, 2000, 2002; Óladóttir et al., 2008, 2006, 2011; Thordarson and Höskuldsson, 2008). Only the paroxysmal phase was modelled and assumed to last between 1 and 4 days stochastically sampled on a uniform PDF. A volume constraint was set between 0.1 and $1\,\mathrm{km}^3$, converted into a mass constraint between 0.7 and 7×10^{12} kg using a bulk density of $700\,\mathrm{kg\,m^{-3}}$. Since no TGSD is available, we used a reconstructed TGSD from the 10 points available for the 1357 eruption in the study of Einarson et al. (1980) using the method of Bonadonna and Houghton (2005), which results in a Md_Φ of -1 and a σ_Φ of 2. However, due to the southward dispersal of the eruption and the narrow area of land between the volcano and the sea, these points present a proximal cross section of the deposit. As a result, a Md_Φ of -1 is considered as a maximum value, and the TGSD adopted here is a Gaussian distribution between -7Φ and 8Φ with Md_Φ sampled between -1Φ and 1Φ, and σ_Φ sampled between 1Φ and 2Φ, both on uniform PDF. The resulting distribution is aggregated with an aggregation coefficient sampled between 20 and 80 %. The same TGSD is used for all occurrences of a given run. The time interval between two occurrences was set to 6 h based on the availability of wind data from the ECMWF database.

Figure 5 and Table 3 summarize the ESP for Katla. Figure 5a shows the resulting PDF for plume heights displaying a slight logarithmic trend, and Fig. 5b shows eruption durations. Figure 5c displays the PDF for the mass sampling of

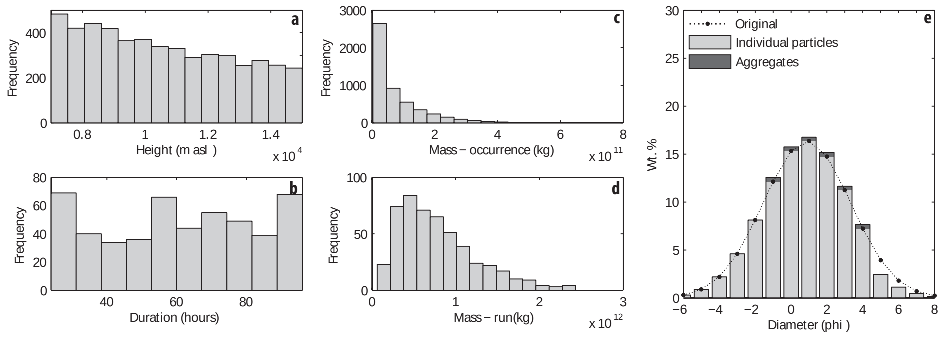

Figure 5. ESP for the Katla LLERS; **(a)** plume heights considering all occurrences (i.e. all model runs); **(b)** eruption duration; **(c)** erupted masses considering all occurrences; **(d)** erupted masses considering single runs; **(e)** example of a TGSD of a single run. See caption of Fig. 4 for explanation of symbols.

individual occurrences and results in a strongly logarithmic shape with masses comprised between 10^9 and 6×10^{11} kg. Figure 5d shows the resulting PDF for the mass per run, and Fig. 5e the TGSD at one of the 1000 runs.

4.1.3 Eyjafjallajökull

The limited knowledge of eruptions at Eyjafjallajökull constrains the identification of eruption scenarios. Two prehistoric eruptions are recognized in the field but poorly constrained and three post–17th century eruptions were witnessed, amongst which the eruptions of 1612 and 1821–1823 lack any constraint. However, since detailed observations and measurements of eruptive parameters exist for the 2010 eruption, we applied here a LLOES strategy in order to assess the entire range of possible hazard related to the occurrence of a similar eruption.

We model here the 40 days of explosive phase that occurred from 14 April to 20 May 2010. The algorithm used is shown in Fig. 2. The total duration, the time series of plume heights and the TGSD are deterministically set a priori. Figure 6a shows measurements of plume heights every 6 h for the 40 days of eruption (Arason et al., 2011), converted into MER using the method of Degruyter and Bonadonna (2012) and wind conditions extracted from the ECMWF database (Fig. 6b). As a result, the time interval between occurrences within a run was set to 6 h. The TGSD used here is as described by Bonadonna et al. (2011), who reconstructed disaggregated and aggregated TGSD by combining ground-based and satellite-based measurements. Here, the same TGSD is used for all runs and does not vary through occurrences.

Following the algorithm in Fig. 2, an eruption date is sampled at each run, after which wind conditions are extracted for the 40 days of the eruption every 6 h. At each occurrence, the MER is calculated accounting for the wind velocity and converted to 6 h averaged mass. The occurrence is sent to the model, and each run is the sum of the 240 occurrences. For computational reasons, it was not possible to run the Eyjafjallajökull probabilistically with FALL3D.

4.1.4 Askja

At least two large tephra deposits associated with strong Plinian eruptions of VEI 5 are recognized at Askja including the 10 ka BP and the 1875 eruptions. Since no accurate mapping or constraints of eruptive parameters are available for the 10 ka BP eruption, we use the 1875 as a reference eruption. Previous studies of Sparks et al. (1981) and Carey et al. (2010) provide an accurate chronology of the different phases of the eruption as well as constraints of the associated eruptive parameters. Two phases are responsible for most of the production of tephra, namely the 1 h long phreato-Plinian phase Askja C followed 6 h later by the 1.5 h long Plinian phase Askja D. As a result, we apply here OES strategies modelling two consecutive eruptions separated by a 6 h break.

Figure 2 shows the algorithm developed for a single OES modelling. Here, the hazard related to a 1875-type eruption consists of the sum of one OES for Askja C and one OES for Askja D. All ESPs (i.e. plume height, erupted mass, eruption duration and TGSD) are fixed deterministically and are summarized in Table 3 and Fig. 7 for both phases. At each run, an eruption date is sampled and wind data for the consecutive phases are extracted. Both TGSD are aggregated with an aggregation coefficient sampled between 20 and 80 %.

4.2 Hazard assessment

This section presents the results of the different model runs for all volcanoes. These results should be viewed as part of a scenario-based hazard assessment, showing the geographical distribution of probability of tephra fallout knowing that an eruption of a given magnitude is occurring. As described in Sect. 3.2, the compilation of probability maps requires a threshold – i.e. either a mass load ($kg\,m^{-2}$), a concentration ($mg\,m^{-3}$), a persistence or an arrival time (h) – in

Table 5. Probabilities, mean arrival time and mean persistence time for a concentration of 2 mg m^{-3} for all FL combined above the selected airports shown in Fig. 1. NR: not reached.

Airport	Eruption scenario	Distance from vent (km)	Concentration probability (%)	Mean arrival time (h ± standard deviation)	Mean persistence time (h ± standard deviation)
Keflavik (BIKF)	Hekla 2000	141	17.0	3.8 ± 2.2	4.7 ± 3.6
	Hekla 1947	141	23.0	3.6 ± 3.2	7.4 ± 5.3
	Katla	178	41.1	24.9 ± 22.2	21.3 ± 15.2
	Askja 1875	303	16.8	9.2 ± 7.7	18.2 ± 12.4
Oslo Gardermoen (ENGM)	Hekla 2000	1635	0.0	NR	NR
	Hekla 1947	1635	0.5	17.7 ± 5.2	4.6 ± 1.9
	Katla	1603	6.7	45.1 ± 21.4	7 ± 5.4
	Askja 1875	1503	11.5	24.6 ± 12.1	6.9 ± 4.3
London Heathrow (EGLL)	Hekla 2000	1780	0.2	11.2 ± 3.2	2.9 ± 0.9
	Hekla 1947	1780	0.8	13.0 ± 3.2	3.4 ± 2.2
	Katla	1731	5.2	47.3 ± 24.4	9.8 ± 8.1
	Askja 1875	1767	8.5	22.6 ± 12.8	7.6 ± 4.4
Amsterdam Schiphol (EHAM)	Hekla 2000	1909	0.1	15.3 ± 0	2.7 ± 0
	Hekla 1947	1909	0.5	15.9 ± 1.0	6.7 ± 3.6
	Katla	1862	7.3	48.6 ± 20.7	9.0 ± 7.1
	Askja 1875	1860	9.7	22.6 ± 7.2	8.0 ± 4.3
Copenhagen Kastrup (EKCH)	Hekla 2000	2000	0.0	NR	NR
	Hekla 1947	2000	0.3	20 ± 0.8	4.4 ± 1.6
	Katla	1938	5.0	50.9 ± 20.6	6.6 ± 4.8
	Askja 1875	1876	6.9	25.9 ± 9.3	6.0 ± 3.1
Paris Charles De Gaulle (LFPG)	Hekla 2000	2136	0.0	NR	NR
	Hekla 1947	2136	0.2	15.8 ± 0.4	3.4 ± 1.6
	Katla	2075	3.7	50 ± 25.8	9.1 ± 8.6
	Askja 1875	2106	8.1	27.6 ± 12.5	6.9 ± 3.7
Frankfurt (EDDF)	Hekla 2000	2223	0.0	NR	NR
	Hekla 1947	2223	0.3	18.7 ± 0.6	5.9 ± 1.5
	Katla	2175	5.2	47.9 ± 21.1	7.7 ± 5.3
	Askja 1875	2175	6.8	27.4 ± 11.7	6.6 ± 3.3

order to calculate the exceeding probability for each eruption scenario. Based on the available literature, we use three relevant thresholds for ground accumulation, one for atmospheric concentration, one for persistence and one for arrival time (Table 4). The Supplement contains the entire collection of maps produced including probability maps for atmospheric concentration as well as persistence and arrival times in terms of mean, standard deviation and probability, computed for all FL and for all critical thresholds. The resulting impact is presented in the companion paper of Scaini et al. (2014).

4.2.1 Ground deposition

Figures 8–11 show the probability maps of exceeding a given threshold of tephra accumulation on the ground for Hekla, Katla, Eyjafjallajökull, and Askja, respectively. In agreement with Fig. 3, there are preferential eastwards dispersals, leaving the Reykjavík area with a negligible probability of being affected by tephra fallout for the volcanoes considered here. As a result, eruptions from volcanoes in the EVZ are likely to affect the area between and east of Gullfoss and Vík í Mýrdal (hereafter referred to as Vík; Fig. 1) (Figs. 8–10).

Figure 8 shows the probability maps for Hekla. Figure 8a and b show the probability of reaching an accumulation of 1 kg m^{-2} for the 2000-type and the 1947-type scenarios, respectively. In the case of a 2000-type eruption, there is a >10 % probability of reaching such an accumulation up to 50 km east of the volcano and a negligible probability to affect Vík. However, Vík and the southernmost coast have a ~ 15 % probability of reaching an equal accumulation for a 1947-type eruption, with the >10 % probability line extending 150–200 km eastwards and 50 km westward from the volcano (Fig. 8b). This scenario has a ~ 10 % probability of producing tephra accumulation of 10 kg m^{-3} in the vicinity of Gullfoss (Fig. 8c) and has a 10 % probability of affecting an area with an accumulation of 100 kg m^{-3} 25 km east of the volcano (Fig. 8d).

Figure 9a–c show the spatial distribution of probabilities of reaching tephra accumulations of 1, 10 and 100 kg m^{-2}, respectively, associated with an eruption at Katla. At Vík, such an eruption results in probabilities of 40 %, ~ 30 %

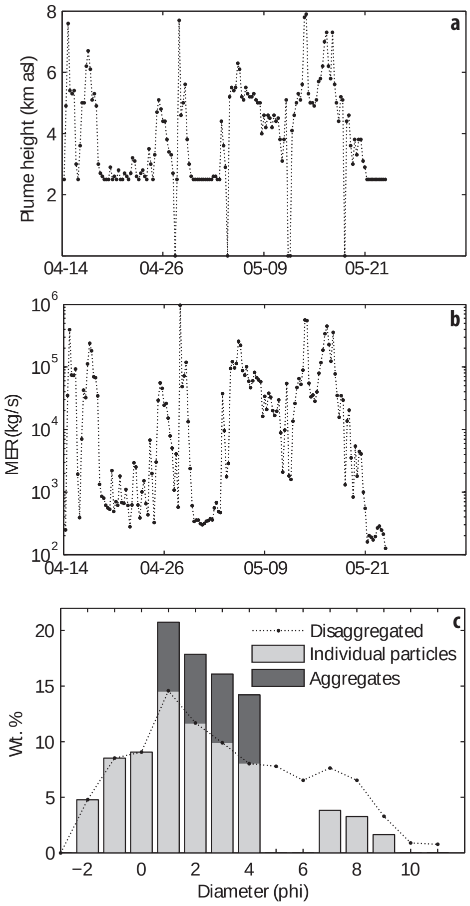

Figure 6. ESP for the Eyjafjallajökull LLOES; **(a)** 6 h interval measurements of plume height for the period 14 April–21 May 2010 (Arason et al., 2011); **(b)** corresponding MER for the same period based on wind conditions extracted from the ERA-Interim database and the method of Degruyter and Bonadonna (2012); **(c)** disaggregated and aggregated TGSD as inferred by Bonadonna et al. (2011). See caption of Fig. 4 for explanation of symbols.

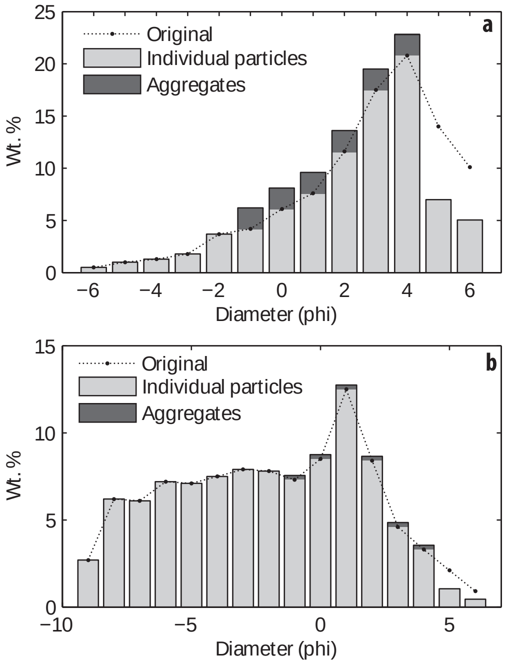

Figure 7. Original and aggregated TGSD of the 1875 Askja eruption based on Sparks et al. (1981) for **(a)** the phreato-Plinian phase Askja C and **(b)** the dry Plinian phase Askja D. See caption of Fig. 4 for explanation of symbols.

and 10 % of reaching tephra accumulations of 1, 10 and 100 kg m^{-2}, respectively. The 10 % probability line of reaching a tephra accumulation of 1 kg m^{-2} extends about 200 km northwards on the mainland and eastwards along the coast.

Figure 10 displays the probability distribution for an Eyjafjallajökull 2010-type eruption, resulting in 80 and 20 % probabilities of reaching tephra accumulations of 1 and 10 kg m^{-2} in Vík, respectively (Fig. 10a and b). Due to the low probability level, the map for an accumulation of 100 kg m^{-2} is not shown.

Located in the NVZ, Askja is most likely to impact the eastern part of the country, with half of the territory having a 5–10 % probability of reaching a tephra accumulation of 1 kg m^{-2} should an 1875-type eruption occur (Fig. 11a). The main town under the threat of an eruption of Askja, Egilsstaðir, has ~ 35 and ~ 15 % probabilities of reaching tephra accumulations of 1 and 10 kg m^{-2}, respectively (Fig. 11a and b). The towns of Akureyri and Húsavik, which both have airports used for internal flights, have 15 and 20 % probabilities of reaching tephra accumulations of 1 kg m^{-2}, respectively. A 1875-type eruption also has a 10 % probability of depositing 100 kg m^{-2} of tephra 50 km east of the vent (Fig. 11c).

Along with probability maps, the hazard related to tephra accumulation can also be expressed as hazard curves, for which the probability of exceeding any tephra accumulation is quantified for a given location. Figure 12 shows hazard curves for relevant eruptions for the locations of Vík, Gullfoss, Akureyri and Egilsstaðir. Although Gullfoss is only a tourist facility, this location was used to assess the probability of tephra accumulation inland. Figure 12a shows that Vík has 15, 40 and 80 % probability of exceeding a tephra accumulation of 1 kg m^{-2} following the considered eruptions of Katla, Hekla 1947-type and Eyjafjallajökull, respectively.

4.2.2 Atmospheric concentration

The hazard assessment for atmospheric concentration is shown in Figs. 13 and 14, Table 5 and the Supplement. For practical reasons, we present here only probability maps accounting for the presence of ash above a threshold of 2 mg m^{-3} at any FL (Sect. 3, Table 4). Arrival time and

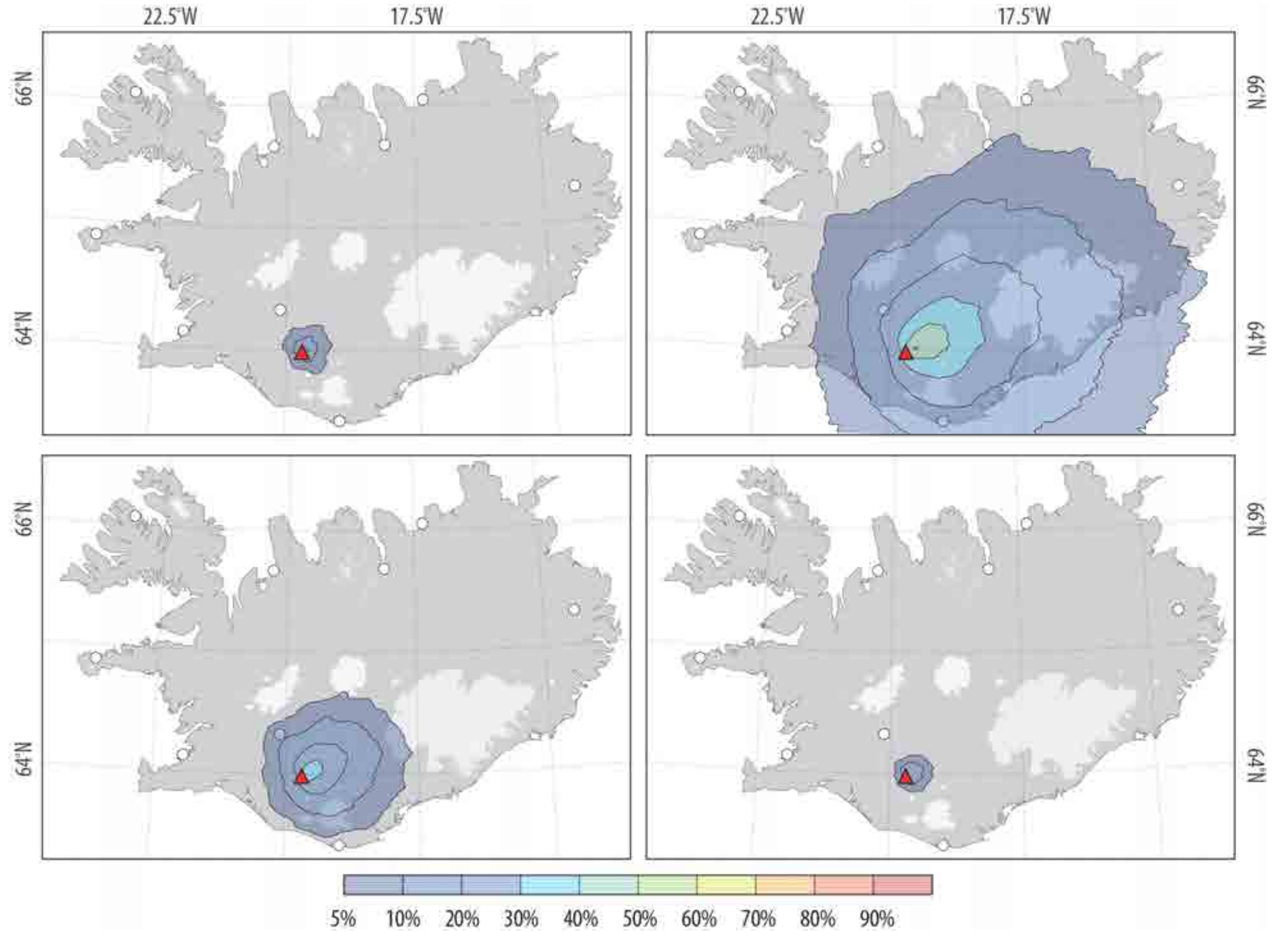

Figure 8. Probability maps (%) for ground accumulation for an eruption at Hekla. **(a)** ERS for a 2000-type eruption, threshold of 1 kg m^{-2}; **(b)** ERS for a 1947-type eruption, threshold of 1 kg m^{-2}; **(c)** ERS for a 1947-type eruption, threshold of 10 kg m^{-2}; **(d)** ERS for a 1947-type eruption, threshold of 100 kg m^{-2}. Eruption parameters are summarized in Table 3 and Fig. 4.

persistence are compiled here in the form of probability maps of exceeding arrival and persistence times of 24 and 12 h, respectively. The choice of 24 h for the threshold of arrival time is based on Guffanti et al. (2010), who showed that 89 % of the aircrafts encounters with volcanic ash in the period 1953–2009 occurred within the first 24 h after the onset of the eruption. Since no threshold of persistence time has been officially outlined, we adopted a threshold of 12 h based on qualitative observations found in the literature (e.g. Ulfarsson and Unger, 2011). The Supplement comprises probability maps for other thresholds (i.e. 2×10^{-6} and 0.2 mg m^{-3}) and for separate FL as well as maps of mean and standard deviation of persistence and arrival time. Due to the high computing demand required to run FALL3D in a probabilistic mode for a 40 day long eruption, the Eyjafjallajökull LLOES 2010-type eruption was omitted from the hazard assessment for atmospheric dispersal.

Figure 13a–c show the results for Hekla. Due to the local dispersal following a 2000-type eruption, only maps for a 1947-type eruption are presented here. Such an eruption would result in a 5–10 % probability of reaching a concentration of 2 mg m^{-3} above the northern Atlantic Ocean and probabilities of reaching London and Oslo of 0.8 and 0.5 % after 13 ± 3 and 17 ± 5 h, respectively (Fig. 13a and b, Table 5). Persistence times for these locations are negligible and are of 3 ± 2 and 5 ± 2 h, respectively (Fig. 13c, Table 5). As shown in the Supplement, similar observations can be made at all separate FLs. These results are in agreement with the findings of Leadbetter and Hort (2011), although differences in scenario identification, modelling strategies and definition of critical thresholds make detailed comparison difficult.

Following the scenario used here, an eruption at Katla has a 5–20 % probability of affecting the UK and Scandinavia with concentrations of 2 mg m^{-3}. Such concentrations are expected to arrive above London and Oslo after $\sim 45 \pm 22$ h

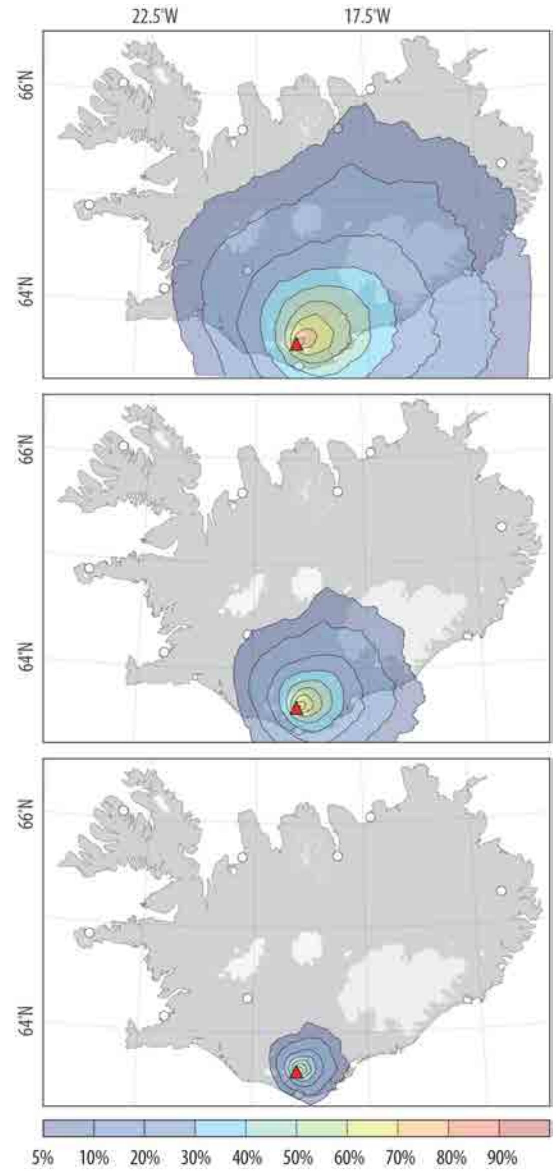

Figure 9. Probability maps (%) for ground accumulation for a long-lasting eruption at Katla. **(a)** LLERS, threshold of 1 kg m^{-2}; **(b)** LLERS, threshold of 10 kg m^{-2}; **(c)** LLERS, threshold of 100 kg m^{-2}. Eruption parameters are summarized in Table 3 and Fig. 5.

in both cases but persist in the atmosphere for less than 10 h (Fig. 13d–f, Table 5). Due to the long-lasting nature of the Katla scenario, note (i) the longer arrival time compared to other eruption scenarios and (ii) the high uncertainty on the mean persistence and arrival time. The Supplement shows that at separate FL, the impacts of a Katla eruption tend to decrease with altitude.

The atmospheric dispersal of tephra following a 1875-type eruption at Askja is presented in Fig. 13g–i, which results in 5–20 % probabilities to reach a concentration of 2 mg m^{-3} over Scandinavia and Western Europe (UK, Northern France, Netherlands, Belgium, and Western Germany). Such a concentration has a 5–10 % probability of reaching the UK and Scandinavia within 24 h, with mean arrival times above London and Oslo of 22±13 h and 25±12 h, respectively (Fig. 13g and h, Table 5). The airports of Paris and Frankfurt can potentially be impacted after $\sim 50 \pm 20$ h in both cases. In all cases, persistence in the atmosphere would be in the range of $\sim$ 6–8 ± 4 h, with a 5–10 % probability of western Norway to be locally impacted by concentrations of 2 mg m^{-3} persisting for more than 12 h. Similar probability distributions, arrival and persistence times are to be expected at all separate FL (see the Supplement).

4.2.3 Short vs. long-lasting eruptions

In order to compare the potential impact resulting from different types of activity at the selected volcanoes (i.e. short- vs. long-lasting eruptions), this section presents deterministic scenarios based on historical and well-constrained eruptions. Note that these simulations do not aim at presenting "worst-case" scenarios, which would require the combined identification of worst-case eruption scenarios and wind condition, but can be viewed as a comparison of key historical eruptions happening under similar meteorological conditions.

The eruptions of Hekla 1947, Katla 1918, Eyjafjallajökull 2010, and Askja 1875 were selected as case-study scenarios for which sufficient data were available to produce a realistic forecast of potential impact. In order to scale and compare the effect of these eruptions, simulations were run using the wind conditions of Eyjafjallajökull 2010, starting from 14 April and lasting for 10 days. ESPs for Eyjafjallajökull and Askja are summarized in Table 3. The 1918 eruption of Katla is the most recent eruption to break through the Mýrdalsjökull ice cap. The available literature suggests that the eruption lasted for 3 weeks, with the most intense tephra production during the first days, plume heights up to 14 km a.s.l. and a total volume varying between 0.7 and 1.6 km^3 (Larsen, 2000; Sturkell et al., 2010). In the absence of any detailed variations of plume heights, radar observations of Arason et al. (2011) were used and scaled to fit observed minimum and maximum plume heights of the Katla 1918 eruption. Using wind conditions specified above and the method of Degruyter and Bonadonna (2012) to estimate the MER, we obtained a total mass of 1.24×10^{12} kg, which is consistent with published volume estimates. Given the similarities between the two systems (Sturkell et al., 2010), the TGSD of Eyjafjallajökull defined by Bonadonna et al. (2011) was also used for this run. ESP for the Hekla 1947 eruption were set using the literature, with a plume height of 27 km a.s.l., a total erupted tephra volume of 0.18 km^3 and a duration of 1.5 h.

Figure 14 summarizes the expected concentrations at FL150 over the main European airport hubs of London

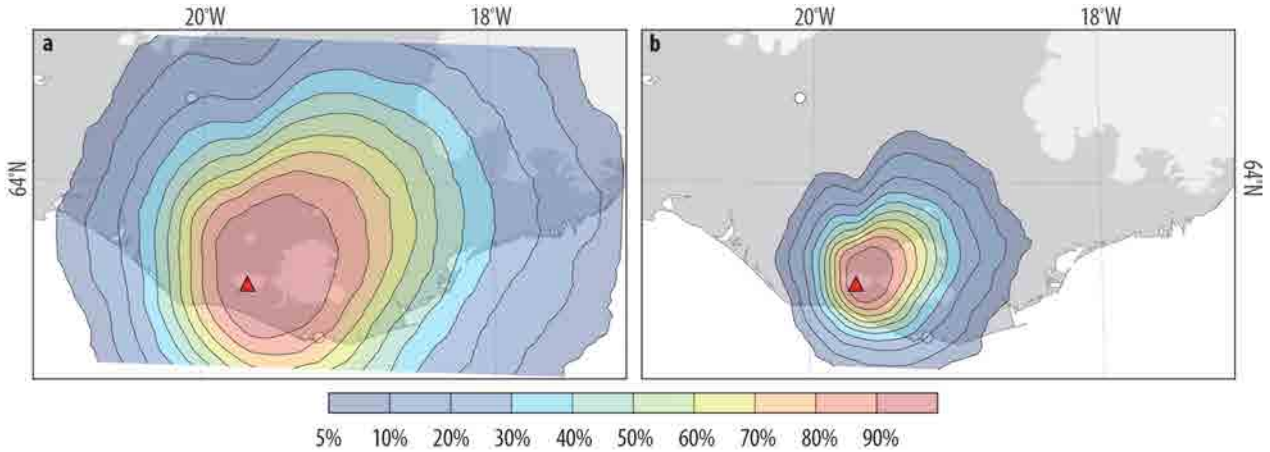

Figure 10. Probability maps (%) for ground accumulation associated with a long-lasting 2010-type eruption of Eyjafjallajökull volcano. **(a)** LLOES, threshold of 1 kg m^{-2}; **(b)** LLOES, threshold of 10 kg m^{-2}. Eruption parameters are summarized in Table 3 and Fig. 6.

Heathrow (EGLL), Paris Charles de Gaulle (LFPG), Amsterdam Schiphol (EHAM), Frankfurt (EDDF) Oslo Gardermoen (ENGM), and Copenhagen Kastrup (EKCH) with wind conditions of April 2010, corresponding to the onset of the explosive phase of Eyjafjallajökull 2010 (see Fig. 1 for locations). When interpreting Fig. 14, one should keep in mind that it represents a slice at FL150, namely an altitude of about 4.6 km a.s.l., and the plume height of each scenario should be put in context when interpreting results. Concentration maps for these scenarios for all flights levels can be found in the Supplement.

Figure 14 shows that a Hekla 1947-type eruption bears the largest impact in terms of airborne concentration. A 1947-type eruption would result in concentrations above the threshold of 0.2 mg m^{-3} over London, Paris, Amsterdam, Frankfurt and Copenhagen (i.e. 0.35–0.68 mg m^{-3}) arriving after 2–4 days and potentially disrupting the air traffic between 1 and 3 days. Oslo would be the most impacted area with concentration peaks above 10 mg m^{-3}. A Katla 1918-type eruption, characterized by a pulsatory regime with repeated emissions of ash, would potentially be most problematic for the European airspace in terms of duration of disruption. Although most likely reaching concentrations comprising only between 0.1 and 0.25 mg m^{-3}, Fig. 14 reflects the repeated arrival of clouds over time and its potential implications for the management of a volcanic crisis. The eruptions of Askja 1875 and Eyjafjallajökull 2010 only seem to be problematic for Oslo, reaching concentrations above 2 and 0.2 mg m^{-3} respectively.

5 Discussion

5.1 Eruption scenarios and probabilistic strategies

Three steps were taken to develop probabilistic hazard scenarios including (i) the identification of the most probable and potentially problematic eruptive styles at given volcanoes, (ii) the development of adapted algorithms to model each eruption type (Fig. 2), and (iii) the definition of eruption scenarios with constrained ESPs (Figs. 4–7). At the selected volcanoes, this led to the identification of both short- and long-lasting eruptions scenarios with both fixed and variable ESP.

5.1.1 Fixed vs. variable ESPs

Amongst chosen volcanoes, a large discrepancy exists in terms of the knowledge of the eruptive history, which is directly related to the frequency of activity during historical times: 17, 10, 3, and 1 eruptions of interest (i.e. explosive eruptions at the central vent) occurred during historical times at Hekla, Katla, Eyjafjallajökull and Askja, respectively. On the other hand, a discrepancy also exists in the degree of detail to which eruptions have been mapped and characterized. For example, the single eruption of Askja is thoroughly characterized in terms of chronology of eruptive phases, plume height, erupted volume and TGSD whereas eruptions of Katla are mainly bounded by rough estimates of volume. As a result, the choice of expressing eruption scenarios as either a single set of ESPs deterministically defined (OES) or as a stochastic sampling on a PDF (ERS) is made upon the combined knowledge of the eruptive history and the degree of characterization of eruptions. The end-user should account for the limitations considered with each approach.

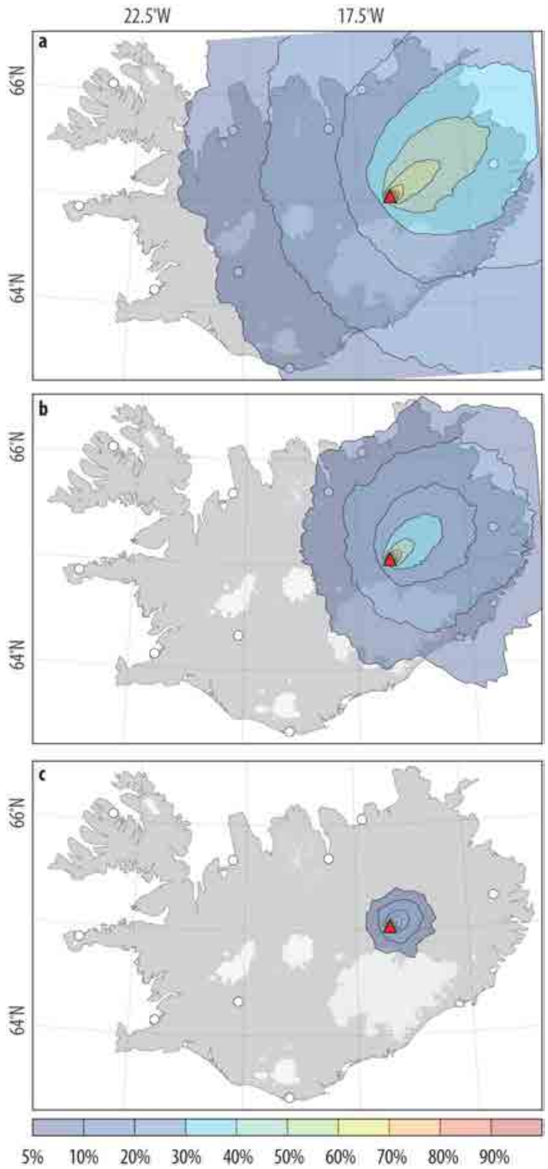

Figure 11. Probability maps (%) for ground accumulation associated with a multi-phase 1875-type eruption at Askja volcano. **(a)** OES, threshold of $1\,\mathrm{kg\,m^{-2}}$; **(b)** OES, threshold of $10\,\mathrm{kg\,m^{-2}}$; **(c)** OES, threshold of $100\,\mathrm{kg\,m^{-2}}$. Eruption parameters are summarized in Table 3 and Fig. 7.

5.1.2 Sampling of ESPs

Figure 2 shows the algorithms used to produce both ERS and LLERS, where the erupted mass is indirectly derived from the plume height, the eruption duration and wind conditions (Degruyter and Bonadonna, 2012) and tested against a mass range. Although the sampling of plume height was constrained on a logarithmic distribution as a prior knowledge, the resulting PDF only including values validated by our algorithm shows a wide variety of shapes. For example, Fig. 4a shows that the initial assumptions of erupted mass (i.e. 6.9×10^9–6.9×10^{10} kg) for a 2000-type eruption at Hekla for a 0.5–1 h long eruption cannot be realistic with plume heights under 10 km a.s.l., resulting in (i) a PDF for plume heights biased towards the largest end-members and (ii) a PDF for erupted mass in agreement with an initial assumption of a logarithmic distribution of ESP. Similarly, the 1947-type scenario results in a PDF with a maximum at plume heights of 18–20 km a.s.l. but without solution for plume heights above 27 km a.s.l. satisfying the initial mass (6.9×10^{10}–3.5×10^{11} kg) and duration (0.5–1 h) conditions (Fig. 4d). As a result, this method accounts for a prior knowledge of the system (i.e. initial choice of a PDF for the sampling of ESP) and helps to correct the sampling of dependent ESPs (i.e. plume height, eruption duration, MER and erupted mass) in order to produce realistic events within an eruption scenario.

5.1.3 Short- vs. long-lasting eruption scenarios

Assessing the hazard related to tephra dispersal from long-lasting eruption is commonly done using non-steady models but rarely using steady models. Scollo et al. (2013) already used the model TEPHRA2 to evaluate tephra hazard associated with long-lasting violent Strombolian activity at Mt Etna, Italy (e.g. the 21–24 July 2001 eruption). They defined it as weak long-lived plume scenario (OES-WLL and ERS-WLL) with an eruption duration of 4–100 days, in contrast to short-lived plume scenarios (OES-SSL and ERS-SSL) associated with the paroxysmal phase of subplinian eruptions (e.g. the 22 July 1998 eruption).

Here, we developed new algorithms for the sampling of ESPs to assess the ground deposition from long-lasting eruptions (Fig. 2). Conceptually, the total ground accumulation calculated with TEPHRA2 consisted of consecutive occurrences of the model run at a given time interval Δt, after which all outputs are summed. With FALL3D, the continuous computation allowed simply updating of the ESPs every Δt without interruption. Here, the typical 6 h time resolution of reanalysis data sets conditioned the duration of Δt, implying constant eruption conditions between either different runs or updates.

5.2 Ground accumulation and atmospheric dispersal

5.2.1 Ground accumulation

Figures 8–11 show that although computed accumulations are not sufficient to cause structural damage to buildings (i.e. $> 100\,\mathrm{kg\,m^{-2}}$), deposition of 1–$10\,\mathrm{kg\,m^{-2}}$ is likely to occur, which is consistent with historical chronicles primarily reporting impacts on agricultural activities (e.g. crops destruction, poisoning of animals; Thorarinsson, 1967; Thorarinsson and Sigvaldason, 1972). In addition, eruptions from

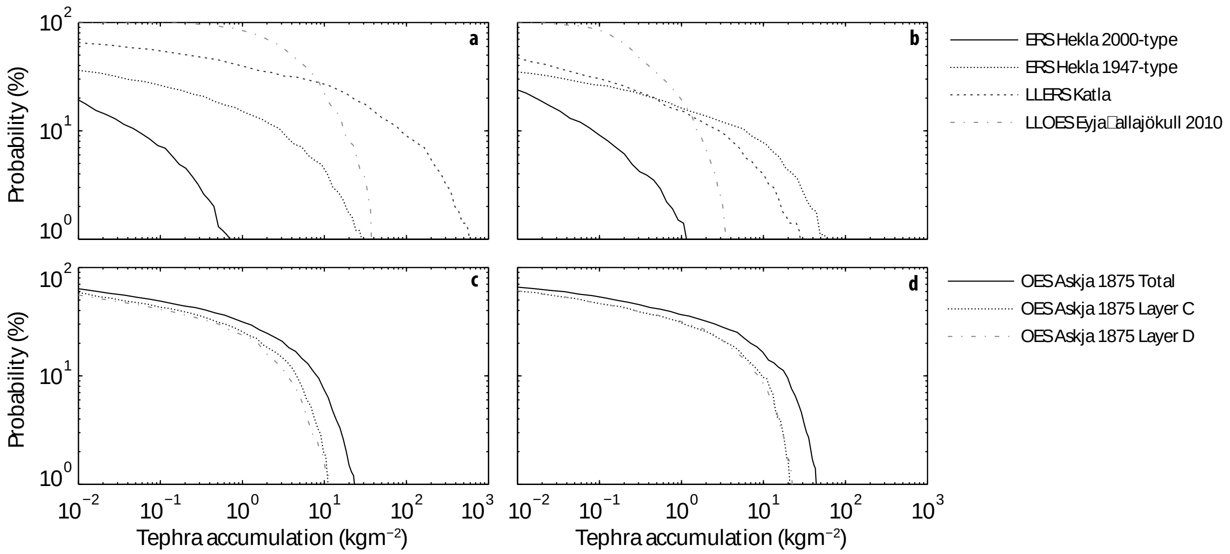

Figure 12. Hazard curves for the locations of **(a)** Vík, **(b)** Gullfoss, **(c)** Akureyri and **(d)** Egilsstaðir (see locations in Fig. 1). Only relevant eruptions are shown at each location, i.e. ERS Hekla 2000- and 1947-type, LLERS of Katla and LLOES 2010-type of Eyjafjallajökull for Vík and Gullfoss and OES 1875-type of Askja (total eruption and individual phases) for Akureyri and Egilsstaðir.

ice-capped volcanoes such as Katla and Eyjafjallajökull are typically associated with jökullhaups, which can cause significant structural damage to buildings, roads and bridges. If these observations are valid for the selected volcanoes and potentially for most of central vent eruptions with VEI up to 5 – excluding maybe the volcanoes located in the vicinity of Reykjavík and Keflavik – "fires"-type eruptions would result in larger magnitude impact. A review of the environmental changes produced by the Eldgjá fires can be found in Larsen (2000).

Hazard maps produced here show preferential dispersals towards the E–ENE, consistent with wind observations (Fig. 3). However, compilations of dispersal axes for historical eruptions are available for Hekla (Thorarinsson and Sigvaldason, 1972) and Katla (Larsen, 2000) and show the existence of deposition in all directions around the vents. For example, only 7 out of the 14 historical eruptions of Hekla were dispersed in directions between 0 and 180°, and 8 eruptions dispersed tephra in a 340–20° sector. Similarly, half of the historical eruptions of Katla were dispersed and deposited with a bearing comprised between 0 and 180°. By comparing our probability maps for Eyjafjallajökull to the isomass maps of Gudmundsson et al. (2012) compiled for land deposition in the period 14 April to 22 May, we observe a ground deposition slightly more directed towards the south than predicted by our model (Fig. 10). However, deposition observed on the ground for both 1 and 10 $kg\,m^{-2}$ (converted from the isopach maps of Gudmundsson et al. (2012) with a density of 1400 $kg\,m^{-3}$) fall between our 10 and 30 % probability lines. Similarly, the isopach maps and ground measurements for the C and D units of the Askja 1875 produced by Carey et al. (2010) are in agreement with our 10 and 20 % probability lines for ground tephra accumulations of 1 and 10 $kg\,m^{-2}$ (Fig. 11).

5.2.2 Atmospheric concentration

Figure 13 summarizes the most likely dispersal trends, in agreement with the wind transect of Fig. 2, and shows that the areas most probably affected by far-range dispersal of ash are Scandinavia and the northern UK. Such results are in agreement with the compilation of the tephrochronological studies of Swindles et al. (2011), who show that the past 7000 years of volcanic activity in Iceland resulted in the identification of 38, 33, and 11 tephra layers in Scandinavia, Ireland and Great Britain, respectively. As suggested by Lacasse (2001), Scandinavia is subject to zonal airflow, whereas Ireland is more likely to be affected than the rest of Europe as it is most probably in the path of anticyclonic airflows from Iceland. As a result, minimum estimates provided by Swindles et al. (2011) show that, based on the record of the past 1000 years, northern Europe is affected by volcanic ash with a mean return interval of 56 ± 9 years and that there is a 16 % probability of tephra fallout every decade based on a Poisson model.

When using a deterministic approach, Fig. 14 shows that amongst the selected eruptions, an eruption of Hekla 1947 is the most likely to produce critical concentrations above the main European airports. Interestingly, scaling Hekla 1947 with the two main phases of Askja 1875 reveals that an erupted volume falling within the boundaries of a low VEI 4 (Hekla 1947) can produce concentrations more than one

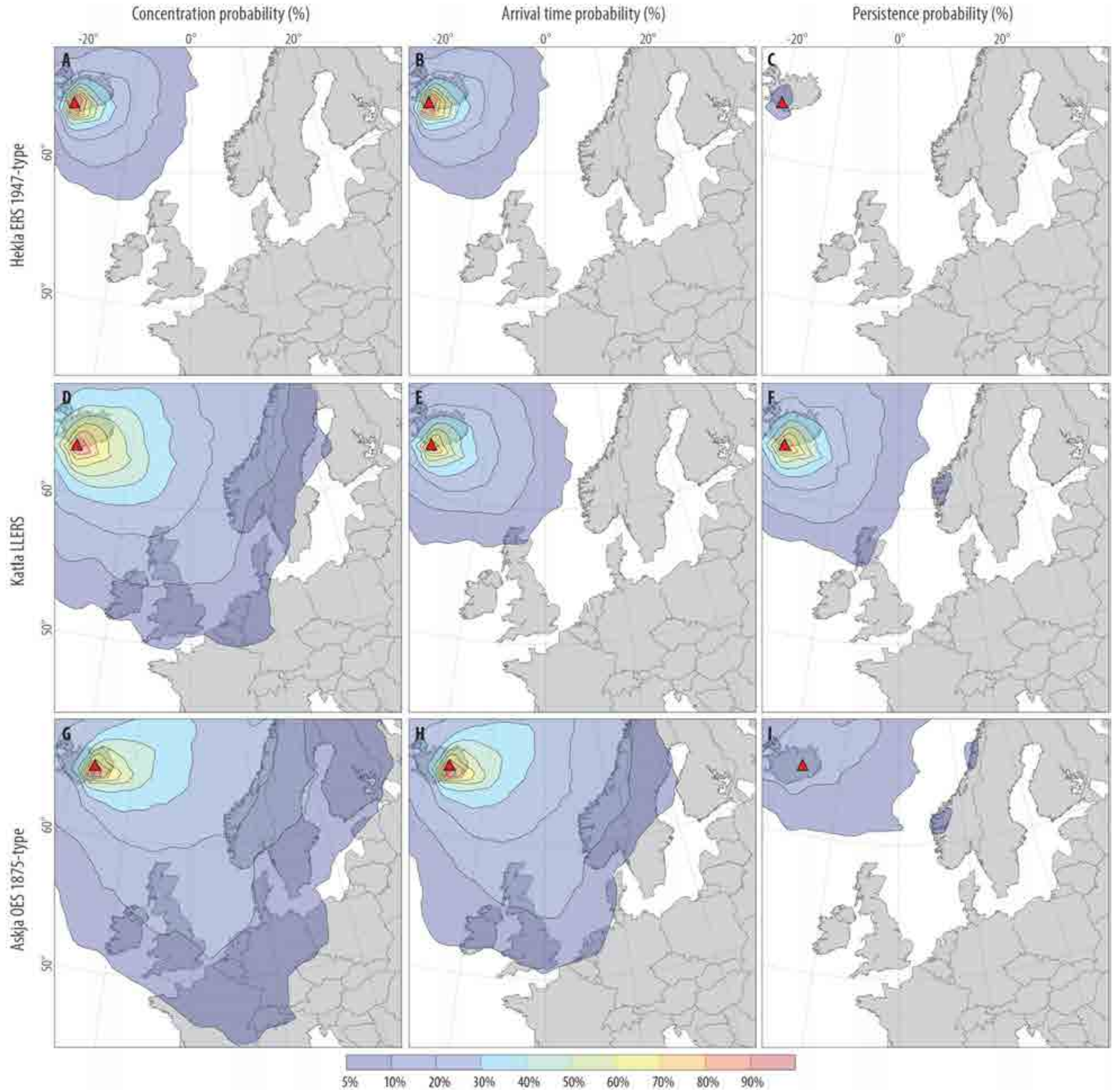

Figure 13. Atmospheric dispersion of tephra for a threshold of $2\,\mathrm{mg\,m^{-3}}$ for all FL for the eruption scenarios of Hekla ERS 1947-type **(a, b, c)**, Katla LLERS **(d, e, f)** and Askja OES 1875-type **(g, h, i)**. Maps show **(a, d, g)** probability maps of exceeding a concentration of $2\,\mathrm{mg\,m^{-3}}$, **(b, e, h)** probability maps of exceeding an arrival time of 24 h for a concentration of $2\,\mathrm{mg\,m^{-3}}$ and **(c, f, i)** probability maps of exceeding a persistence time of 12 h for a concentration of $2\,\mathrm{mg\,m^{-3}}$. Probability maps for other thresholds and separate FL are available in the Supplement.

order of magnitude larger than an eruption of low–medium VEI 5 (Askja 1875). For example, London Heathrow would suffer ash concentrations of 0.68 and $0.025\,\mathrm{mg\,m^{-3}}$ following eruptions of Hekla 1947 and Askja 1875, respectively (Fig. 14). Similarly, Davies et al. (2010) report that five eruptions of Hekla with volumes varying between 0.18 and $0.33\,\mathrm{km^3}$ produced tephra beds in Norway, Scotland and Finland, more than 1500 km beyond the source. Such observations support the growing idea that the tephra volume of an eruption is not the primary factor controlling the distal dispersal of fine ash and that the TGSD, the nature of the fragmentation process (i.e. dry vs. phreatomagmatic) and the

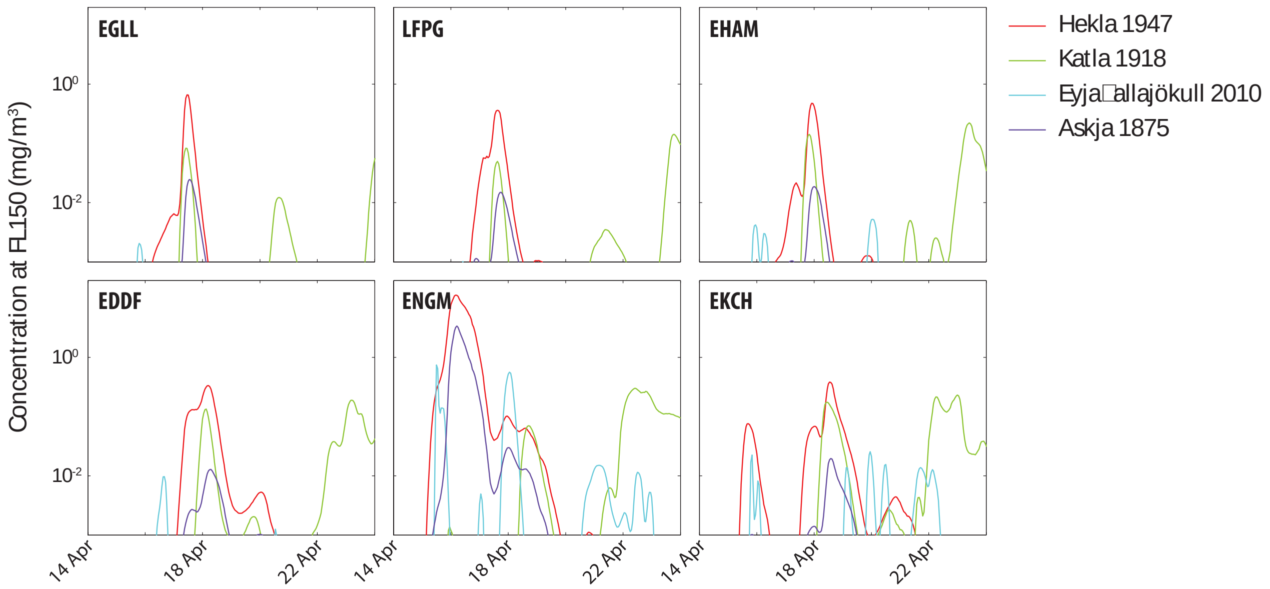

Figure 14. Airborne concentration of ash at FL150 above the airports of London Heathrow (EGLL), Paris Charles de Gaulle (LFPG), Amsterdam Schiphol (EHAM), Frankfurt (EDDF), Oslo Gardermoen (ENGM) and Copenhagen Kastrup (EKCH) resulting from the eruptions of Hekla 1947, Katla 1918, Eyjafjallajökull 2010 and Askja 1875. Each eruption was run for 10 days starting from 14 April 2010 using similar wind conditions that occurred during the Eyjafjallajökull 2010 eruption. Concentrations for other FL can be found in the Supplement.

weather patterns play important roles (Davies et al., 2010; Swindles et al., 2011).

The concept of defining critical thresholds, typically 0, 0.2 or $2\,\mathrm{mg\,m^{-3}}$ depending on the approach adopted, implies that the hazard level is at its maximum once the concentration threshold has been reached. If, for instance, a value of $0.2\,\mathrm{mg\,m^{-3}}$ is adopted as critical, the shape of the curve above the threshold for the eruption of Hekla 1947 displayed on Fig. 14 does not provide any relevant information as the level of maximum impact is reached. However, for crisis management purposes, the duration during which concentrations are above the threshold becomes critical. In this perspective, the eruption type has a major control on the hazard and the potential associated consequences. For example, concentration plots using a deterministic approach for all flight levels shown in the Supplement illustrate how short-lasting and intense Plinian eruptions result in single peaks of critical concentration typically lasting for a couple of days, reaching up to $12\,\mathrm{mg\,m^{-3}}$ above the Oslo airport following a Hekla 1947 eruption. In contrast, an eruption of Katla 1918, although not reaching such high levels of critical thresholds, results in more diffuse signals spanning over longer periods of time over single geographic points. When considering a 3-D volume above the European territory representing the airspace and observing the potential disruptions from a management perspective, continuous emission of tephra with a pulsatory regime, though not producing the high concentrations of Plinian eruptions, are potentially able to become more problematic than short-lasting powerful eruptions.

6 Conclusions

The present work highlights the challenges of achieving a multi-scale hazard assessment from multiple and heterogeneous sources in order to compare and combine outcomes of the most likely range of possible eruptions. For the selected volcanoes, we could define both semi-probabilistic (i.e. stochastic sampling of wind conditions and ESP deterministically fixed) and fully probabilistic (i.e. stochastic sampling of both wind profiles and ESP) eruption scenarios based on the available data. In each case, we developed new algorithms to assist the identification of eruption parameters for both short- and long-lasting eruptions, which help to achieve the sampling of realistic ESP and account for particle aggregation processes. For the atmospheric dispersal of fine ash, a sound deterministic approach demonstrated the different hazards posed by short- and long-lasting eruptions and showed the importance of the potential disruption time over high concentrations. As a result, the outcomes of this work constitute a first step towards an improved management of future volcanic crises, accounting for most critical aspects of both the geological and atmospheric science sides of the problem. The second step toward a sound impact and risk assessment typically involves the identification of the exposed elements and their vulnerability to the stress constituted by ground tephra accumulation and distal atmospheric ash. Such an approach is tackled in a companion paper by Scaini et al. (2014).

In terms of hazard assessment, we can conclude that:

- Eruption scenarios and ESP must be defined using probabilistic strategies based on strong field observations.
- Based on our probabilistic scenarios (e.g. OES, ERS), Askja represents the most hazardous volcano.
- Based on our deterministic scenarios, Hekla is likely to produce the largest atmospheric concentrations of ash but Katla will result in longer disruptions of air traffic.
- At the Icelandic scale, expected accumulations will mainly be a concern for electrical power-lines and agricultural activities (i.e. accumulations of $10\,\mathrm{kg\,m^{-2}}$).
- Our empirical approach to describe aggregation, although simplistic, is a suitable field-based method for computationally heavy probabilistic analysis, which allows the investigation of a wide range of aggregation conditions.
- Results suggest that the erupted tephra volume is not the primary control on the dispersal, whereas the eruptive style (i.e. long-lasting vs. short-lasting) and the TGSD (i.e. fine vs. coarse distributions) might play primary roles.

The Supplement related to this article is available online at doi:10.5194/nhess-14-2265-2014-supplement.

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The role of GIS in multi-scale impact assessment of explosive volcanic eruptions: case-study of Concepción volcano, Nicaragua.

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The role of GIS in multi-scale impact assessment of explosive volcanic eruptions: case-study of Concepción volcano, Nicaragua.

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1. Introduction

The main topic of this work is the impact of explosive volcanic eruptions on the anthropic system, at both local and global scale. When an explosive volcanic eruption takes place, a huge quantity of tephra is ejected. The coarse fraction is soon deposited at ground, while fine ash can remain airborne from days to weeks.

Impacts of tephra deposition are quite well-studied. Ash deposition can damage to structures (Spence et al., 2005a,b;), lifelines (Johnston and Becker, 2001; Stewart et al., 2006), impact crops and kettle (Neild et al., 1998), disrupt road traffic (Wilson et al., 2012) and cause the closure of airports (Casadevall, 1993; Guffanti et al., 2009). Finally, massive tephra deposition can produce respiratory problems on vulnerable subjects (Baxter, 1999).

There are only a few studies on impacts of atmospheric tephra dispersal. The main impact of ash contamination in atmosphere is the disruption of aerial traffic (Guffanti et al., 2009). Impacts of volcanic ash have been documented in the past (Casadevall, 1993), but underestimated until recently. The volcanic eruption of Eyjafjallajokull (Iceland, 2010) produced the largest breakout of civil aviation in Europe after the II World War. This event underlined the high vulnerability of aerial traffic, and showed that weak eruptions can cause massive economical losses and affect the entire society (Mazzocchi et al., 2010; Ulfarsson and Unger, 2010). It is therefore important to characterize the active volcanoes, assess the expected impacts and improve preparedness.

This abstract will briefly describe the hazard assessment and impact estimation for a case-study: Concepción volcano, Nicaragua. The idea started from a field trip to Ometepe Island (November 2010), constituted by the twin stratovolcanoes Concepción and Maderas. Concepción volcano has been quite active in recent years (Delgado-Granados et al., 2006). Ometepe island is highly vulnerable at a local scale, and the aerial traffic of the region is relevant for tourism and commerce. An explosive eruption from Concepción volcano could produce serous consequences at both local and regional scale. We perform the hazard assessment (Scaini et al., 2012) and assess the vulnerability at local and regional scale. We produce hazard and vulnerability maps for local and regional scale. All maps are produced through the open GIS Grass (Neteler et al., 2011) and Qgis (http://www.qgis.org/).

Having characterized the hazardous phenomena and the vulnerability, the impacts can be seen as their "combination", that is, the spatial overlap. The GIS, due to its enormous capabilities of handling spatial data (Renschler, 2005), is especially suitable for this task. There are few examples of volcanic hazard assessment (Felpeto et al., 2007) and impact estimation of tephra deposition (Biass et al., 2012) based on GIS, while it has never been used for the assessment of tephra dispersal impacts.

The GIS-based visualization allows to identify the most impacted areas and assess the expected impacts at local and global scale. The aim of future work is to produce impact maps at local and regional scale. At the moment, we present some preliminary results and briefly discuss their implication for local and regional risk management. We conclude proposing further developments for the integration of GIS in the risk management process.

2. Hazard assessment

Hazard assessment is the procedure of characterization and modelling of the expected eruptive scenarios. The hazard assessment methodology and its application to Concepción volcano is fully described in Scaini et al. (2012). We run several simulations for each scenario, using the Fall3d numerical model (Costa et al., 2006; Folch et al.,2009). Hazard maps are produced by merging the results and calculating the probability for each point to be affected by a critical value of ash load or concentration. We produced probabilistic hazard maps of ash load at ground for the critical values of 1 kg/m^2 (which corresponds to road traffic disruption, crops and kettle damages), 50 and 100 Kg/m 2 (collapse of weak and stronger buildings, respectively). Moreover, we produced maps of ash concentration at different flight level, using the thresholds of 0.2 mg/m^3 and 2 mg/m^3 (restricted aerial traffic and no-fly zone, respectively). Figure 1 shows the results of hazard assessment for the higher-magnitude scenario (described in Scaini et al., 2012) for tephra load at ground. Figure 2 shows results at Flying Level (FL) 050 and 150.

3. Vulnerability and impact assessment

The vulnerability and impact assessment are performed at local and regional scale. Ometepe Island is highly vulnerable due to several factors. First, the fact of being an island increases the vulnerability. The connection to the mainland mainly depends on private boat services, which is strategical for the island communities. The situation of internal transportation is critical because the road networks is constituted by one main circumambulation road and lacks of redundancy. Buildings are weak and in their majority poorly maintained. Moreover, the steep flanks of Concepción volcano are likely to generate landslides, especially during the rainy season. With a scarce transportation network and few alternative paths, the occurrence of a landslides can cut a road and aisle entire communities. Figure 3 shows the vulnerability maps produced at the moment for the local assessment, synthesizing the main features considered (population, roads, crops). From a regional point of view, the main strategical airport of the area is Managua International Airport, located at only 100 km from Concepción. Moreover, the new airport being built in Ometepe is clearly vulnerability due to its location. Having identified the main airports of the area, it would be suitable to rank them according to their importance. At the moment, data about passengers and freight traffic are not available for the area, but we are starting a collaboration with local authorities.

4. Results and discussion

The overlap of hazard and vulnerability maps allows to estimate the expected impacts. Maps of expected impacts cannot be produced at the moment. Preliminary results of local impact assessment can be inferred from Table 1. Tephra deposition can produce damages to crops in the island and the rest of the region. Moreover, tephra accumulated in the flanks of the volcano can produce landslides, especially during the rainy season. The situation of the road network can therefore become critical. The analysis of impacts is still ongoing and will likely produce an expected impact map, underlining the critical areas.

Table 2 shows the probability of closure of the aerial space during an high-magnitude explosive eruption at Concepción volcano. With data on aerial traffic, one could assess the number of disrupted flights and the passengers stranded. It is worth to note the high impact of volcanic activity on the new airport which is currently being built near the town of Moyogalpa. Moreover, some of the considered airport are strategical for the Nicaraguan economy, especially for the tourism and the trade of perishable goods.

This work shows the importance of GIS to display and analyse spatially-based information in the field of volcanic risk-management. GIS enhances the communication process, improves the information flow and supports decision-making. Finally, the use of Open Source GIS allows an advanced control of functions and guarantees the interoperability with other programs.

5. Figures and tables

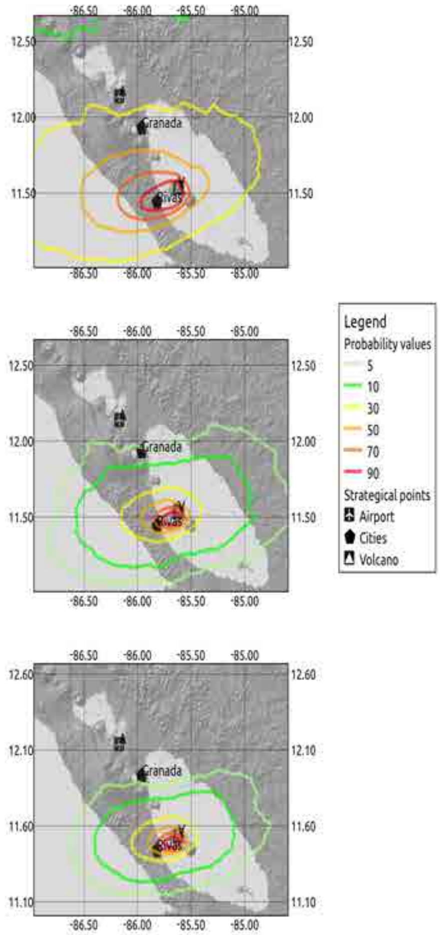

Figure 1: results of hazard assessment for tephra load at ground, for values of 1 (top), 50 (middle) and 100 (bottom) kg/m² respectively.

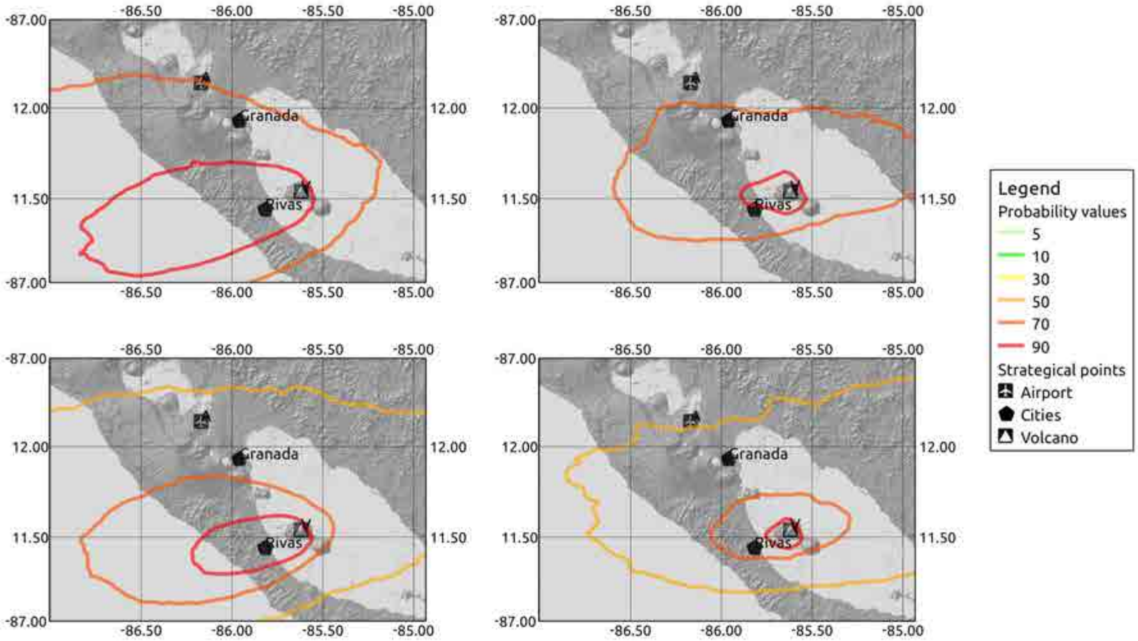

Figure 2: results of hazard assessment for tephra dispersal at FL050 (top) and 150 (down), for the critical value of 0.2 mg/m³ (left) and 2 mg/m³ (right) respectively.

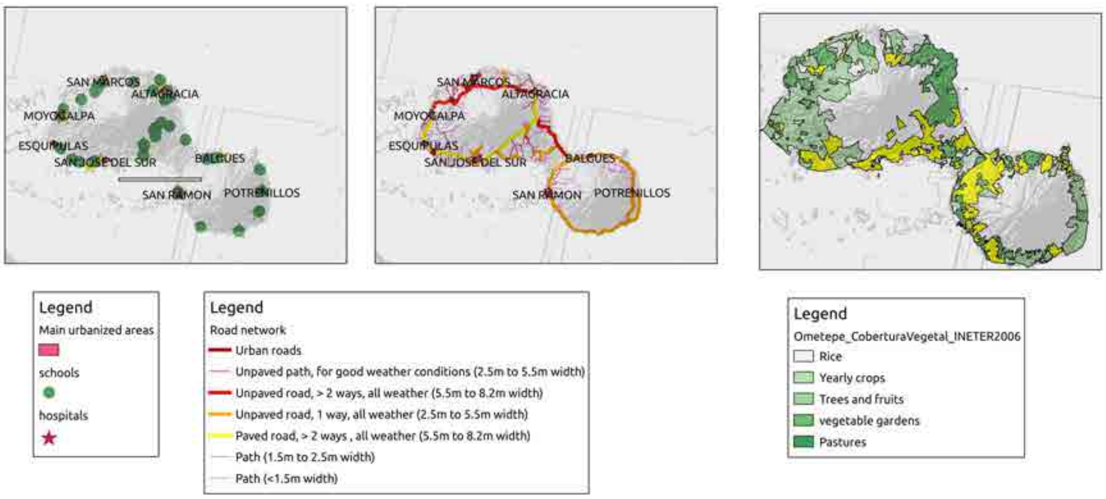

Figure 3: Synthesis of vulnerable elements at local scale. Strategical points and population (left) and roads classification (right).

	Ground load			Concentration at FL050		Concentration at FL150	
	1 kg/m²	50 kg/m²	100 kg/m²	0.2 mg/m³	2 mg/m³	0.2 mg/m³	2 mg/m³
San Jose del Sur	100	99	98	100	100	100	100
Esquipulas	99	98	91	100	100	95	95
Moyogalpa	99	91	79	100	100	97	93
Rivas	97	56	46	99	99	86	75
Granada	~ 0	~ 0	~ 0	77	65	74	55

Table 1: Table 2: Probability of having a tephra accumulation at ground of 1, 50 and 100 mg/m³ at the main airports of the region (results for high-magnitude scenario).

	Concentration at FL050 2 mg/m³	Concentration at FL050 2 mg/m³
Managua Airport	57	50
Corn Island	36	43
Bluefields	40	47
Los Chiles	34	37
Liberia International	30	30
Riofrio Progreso	22	24
Barra colorado	22	27
Guapiles	16	18
Tegucicalpa	~10	~10
Tomalapa International	~10	~10
Puerto Cabezas	~10	~10

Table 2: Probability of having a concentration of 2 mg/m³ at the main airports of the region (results for high-magnitude scenario).

6. Acknowledgements

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A GIS-based tool for the estimation of impacts of volcanic ash dispersal on European air traffic.

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A GIS-based tool for the estimation of impacts of volcanic ash dispersal on European air traffic

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***Abstract*—Impacts of volcanic ash on air traffic have been reconsidered in the aftermath of the 2010 eruption of Eyjafjallajökull volcano (Iceland), which caused great impacts to the European air traffic network. We present a GIS-based methodology to estimate the impacts of tephra dispersal from explosive volcanic eruptions aimed at improving air traffic management in case of ash-contaminated airspace. We use the 2010 Eyjafjallajökull eruption as a case study with two main objectives: to introduce the methodology and to perform *a posteriori* analysis of the 2010 aviation breakdown. Modelling results of atmospheric tephra dispersal over Europe build upon a reanalysis dataset of meteorological and volcanological parameters. Given that there is still no consensus on thresholds of ash concentration that is critical for flight safety, the methodology takes into account several ash concentration values. Results are hourly tables and maps containing information on potentially affected airports and routes at different Flight Levels (FLs). This allows estimating impacts at a high temporal frequency. We also compute daily-accumulated impacts for each FL. We compare our results with the 2010 impacts. Furthermore, advantages and disadvantages of this methodology are discussed and compared with similar existing tools. Finally, we underline possible improvements of the methodology and describe further work.**

I. Introduction

Tephra dispersal is a common phenomenon during explosive volcanic eruptions and can affect downwind areas at regional to global scales. It is well recognized since the first serious jet engine aircraft encounter with ash in the 80s [9] that ash contamination of airspace can cause short to long-term disruptions to airports and aircraft. The knowledge in this field has been systematized during the last decades [9], [8], [23], [21], but the sistemic impacts were underestimated until the Eyjafjallajökull eruption [3], which lasted 4 weeks between April and May 2010 and caused the largest civil aviation breakdown after World War II. It is estimated that this event provoked 2.6 billion US$ losses in Europe and impacted regional and global economy [29] highlighting the high vulnerability of European air traffic network, particularly to long-lasting volcanic eruptions [3].

The 2010 Eyjafjallajökull eruption triggered a change of procedures in the volcanic ash events in Europe. In fact, the procedures in effect in 2010 were put in discussion [3]. The precautionary "zero tolerance" paradigm [23] showed its limitations for an effective management of the European airspace. During the eruption, the closure of airspace in presence of low concentrations of ash was strongly criticized. On 19^{th} May 2010, the European Aviation Crisis Coordination Cell (EACCC) was established, with the aim to improve preparedness, enhance current procedures and ensure cooperation for an integrated risk management [26]. One of the changes was the introduction of the ash concentration charts, based on quantitative thresholds. The zones of lower concentration would not be closed to air traffic, but the operations are subject to the Safety Risk Assessment [3], [7].

In May 2010, the International Civil Aviation Organization (ICAO) established the International Volcanic Ash Task Force (IVATF). The IVATF comprises experts from different fields and identified the stakeholders' needs for the effective management of civil aviation during explosive volcanic eruptions. One of the most critical issues was recognized to be the estimation of ash concentration tolerance of turbines and the definition of ash concentration thresholds [24]. Quantitative thresholds were first suggested by UK MET Office, accepted by EACCC [7] and then modified by the ICAO International Volcanic Ash Task Force [26]. There is still no consensus on the critical values [3] and, although several tests are being performed by manufacturers [12], this remains an open issue.

At present, there are only a few examples of air traffic management procedures linked closely with volcanic ash monitoring systems. Probably, the most advanced system for managing air traffic operations in presence of volcanic ash is the one implemented at the "Istituto Nazionale di Geofisica e Vulcanologia" (INGV) in Catania, Italy [31]. Seismic and plume monitoring are combined with ash dispersal models for different eruptive scenarios to provide dispersal forecasts every 12 hours. The system helps in managing airspace closure in case of ash contamination from Etna volcano. During the 2010 aviation breakout, local response strategies were developed, some being very effective in the mitigation of impacts. For example, the Icelandic company Icelandair managed to move some aircraft from Keflavik (Iceland) to Glasgow (UK), lowering the impacts of ash contamination and maintaining their routes to North America opened [34]. During the 2011 eruption of Cordón Caulle (Chile) [16], [1], Aerolinas Argentinas and LAN Chile declared that a large percentage of economic losses were caused by their fleet being blocked at Bariloche airport, closed for months [2]. This issue could have been better managed with a timely action allowing part of the fleet to be moved elsewhere.

These examples underline the need for methodologies and systems to support mitigation strategies, and many times reiterated request for a higher degree of freedom in the decision-making and management during these events by the airlines. During the 2010 Task force meeting [26], the idea that airlines should be able to decide whether to fly or not in an airspace for which is forecasted to have volcanic ash was expressed. This procedure was then implemented during the 2011 Volcanic Ash Exercise (VOLCEX) [20], an exercise that is performed once or twice yearly in the ICAO European and Northern Atlantic Region with the objective of improving the response to volcanic eruptions and volcanic ash contamination. At present, specific strategies may be applied by any airline, after having presented and approved a Safety Risk Assessment (SRA) [4], [13].

Here we present a methodology for a preliminary estimation of ash dispersal impacts on civil aviation. Ash dispersal maps and air traffic data are combined to estimate expected impacts in form of maps, plots and tables. The methodology is implemented within a Geographical Information System (GIS) that allows effective data management, visualization and post-processing of results [28]. This is the first time that a GIS-based tool is used to assess impacts of ash on civil aviation. The only comparable tool is EVITA (European crisis Visualization Interactive Tool for ATFCM), a map-based tool developed in 2010 by EUROCONTROL and used during the last three VOLCEX exercises and the Grimsvötn eruption in 2011 [3], [4], [32]. EVITA acts as a web-based tool and provides graphical visualization of VAAC's ash charts, produced every 6 hours. Moreover, it is linked with the EUROCONTROL's flight plan database and allows the visualisation of the impacted flights in both horizontal and vertical planes. The advantage of our methodology is that it allows estimating hourly impacts by analysing every time step of the ash dispersal forecast. We apply the methodology to the 2010 Eyjafjallajökull case-study and discuss the implications of results for European air traffic management.

II. Tephra dispersal modelling

The 2010 Eyjafjallajökull eruption has been modeled using different Tephra Transport and Dispersal Models (TTDMs) [16], including those running at the London and Toulouse Volcanic Ash Advisory Centers (VAACs), responsible for issuing volcanic ash advisories in Europe [22]. For example, Folch et al. [17] simulated 10 days of the eruption (from 14^{th} to 24^{th} April 2010) using the FALL3D model [10], [18]. The meteorological dataset was the ECMWF (European Center for Medium-range Weather Forecasts) Era-Interim reanalysis, produced for a computational grid having horizontal resolution of 0.25^{o}. The volcanological inputs relied on hourly-averaged radar observations of plume height [17] and characterization of the ejected material [6], [11]. It should be noted that, because *a posteriori* simulations use better-constrained (defined) meteorological and volcanological model inputs, it comes at no surprise that outcomes from reanalysis simulations can be different from those of forecasts.

Results from TTDMs are a necessary input for subsequent impact assessment, but transferring results to the decision-makers is not straightforward. In fact, numerical models produce a large amount of information, usually stored in compact binary formats. Here we automatically generate digital ash concentration maps for each time step and vertical level considered. There are several tools that support post-processing of modelling results, e.g GRASS GIS [28]. Given that we combine ash concentration maps with air traffic data at selected Flight Levels (FLs), model results are extracted the vertical level closest to each FL. On the other hand, because ash concentration thresholds are still undefined, we contemplate three different values associated to no-ash, 0.2, and 2 mg/m^3 concentration respectively. This approach has been already adopted by recent hazard assessments from tephra dispersal [19], [30], [33].

III. Data management

We use two types of air traffic data: spatial data in the form of GIS maps and air traffic data in the form of database tables. Spatial data is processed and visualized by two common GIS software: GRASS GIS [28] and QGIS (www.qgis.org), both open source. Air traffic data is managed and analyzed using tailored python codes (www.python.org). Queries are performed in Structured Query Language (SQL).

A. Spatial data

Spatial data is constituted by GIS maps containing the main European airports and route trajectories, provided by EUROCONTROL. For simplification, we consider only airports located in the European area and routes that connect the selected European airports. We use air traffic data for 14^{th} 2010, corresponding to the eruption onset. In total, the input database for the impact assessment methodology contains 1264 airports and 22494 flights. Airports and flights are identified in both spatial database and tables by unique identification (ID) codes [14].

B. Air traffic data tables

We used air traffic data from the EUROCONTROL Demand Data Repository (DDR), in particular from the M1SO6 database that contains the last filed flight plans for all flights in the European airspace [14]. Air traffic on Wednesday 14^{th} April 2010 was normal, with a total of 28157 flights, while on 15^{th} and 16^{th} of April the number of flights dramatically decreased due to the applied restrictions in Northern Europe (I). On 17^{th} and 18^{th} April, the European air traffic continued to decrease. From 17^{th} April, the European air traffic saw a dramatic breakdown that lasted until the 21^{st} of April. The rating of the day in the monthly rank (column "Position" in Table I) underlines the evolution of the crisis, showing that the days 17^{th} and 18^{th} had the lowest air traffic values in April 2010.

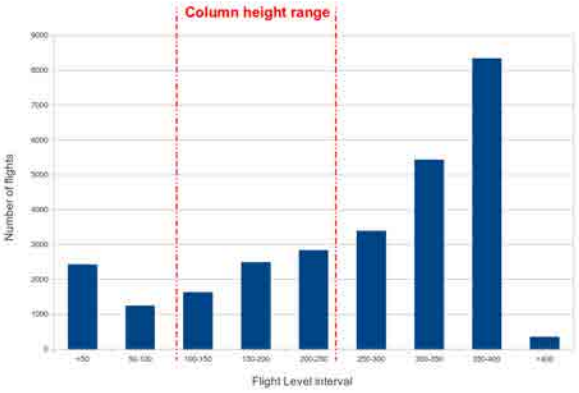

Fig. 1. Flight level statistics for European flights for 14^{th} April 2010. The histogram shows the numbers of flights (identified by an unique Flight ID) having the cruise altitude in each FL interval. Dashed lines show the range of eruptive column height [17]

The day 14^{th} April, used in our analysis, is one of the top-10 days for April 2010, and therefore can be a representative day for April air traffic in Europe. Assuming that air traffic patterns on week days in the same period are similar, air traffic data for 14^{th} April 2010 is used to estimate the impacts on air traffic for the 15^{th} and 16^{th} April. Having discarded extra-European flights, we take into account the 22494 flights contained in the spatial database. Air traffic data consists of flight profiles that are stored as 4D trajectories composed of a sequence of segments, each having start and end time, length and Flight Level (FL) (see [14] for details). An analysis of 14^{th} April air traffic was performed in order to identify the strategic FLs. For each flight, all the trajectory segments are extracted, and the most frequent value of FL in the en-route flight phase is determined. For very short flights, when no value appears to be the most frequent, we take the maximum FL value.

As the en-route phase is characterized by the relatively constant altitude, we take the extracted most frequent (or maximum for short flights) FL value as a constant en-route FL in our methodology. Fig. 1 shows the distribution of estimated en-route altitudes grouped by FL intervals for 14^{th} April 2010 air traffic data. This plot underlines the importance of FLs in the range 300-400, that together account for approximately 50% of the total flights. Given that we do not expect to have critical ash concentration at upper FLs [17], we include FLs 150, 200 and 250, that were strongly impacted during Eyjafjallajökull eruption, and together account for approximately 20% of total flights. The flight levels considered are therefore FL150, FL200, FL250.

TABLE I
NUMBER OF FLIGHTS DURING APRIL 2010 AND MONTHLY RANK OF THE DAY.

Day	Flights	Position
13	27550	12
14	28157	9
15	20528	25
16	11596	27
17	5296	29
18	5291	30
19	9504	28
20	13261	26
21	22159	22
22	27241	14

IV. METHODOLOGY

For each hour, the area with critical ash concentration is overlaid with the air traffic features (airports, routes) and the disruptions are quantified. A GRASS script performs, for each hour, three main operations: data extraction, overlap of hazard (ash concentration) and air traffic data, and production of results in form of tables. All extractions are performed using SQL queries embedded into GRASS scripts.

A. Disrupted airports

The disrupted airports are identified by overlapping the critical hourly ash concentration map and the digital map of European airports. Impacted airports are the ones overlaid by the ash cloud at the FLs 050, 100 and 150, where take-off and landing operations occur.

Airports are stored as points in the GIS database, but we create a circular buffer of user-defined radius surrounding each airport, in order to account for its spatial extension. For each time step, we produce a table containing the characteristics of the airport (ID code, position). The unique ID code can be used to connect this table to other databases and support specific analyses.

B. Impacted flights

Disrupted flights are identified by overlapping the critical ash concentration map and the digital map of routes, for each hour and at each FL considered. The procedure is performed in 5 steps that are repeated for each FL and concentration thresholds:

1) We extract the flights scheduled in the given hourly interval. An automated SQL query selects all flights passing at $\pm$ 3000 feet from the FL for which the ash concentration is calculated. We allow an overlap of 1000 feet between adjacent FLs, that is, some routes are extracted two times, for upper and lower FLs. Although this could lead to a slight overestimation of impacts, this procedure allows accounting for the vertical uncertainties on cloud location, related to the modelling output.
2) We overlap selected flights at FL $\pm$ 3000 ft and ash concentration chart, identifying the ones that may be impacted.
3) For the intersected flights, we extract the waypoints and the corresponding segments scheduled for the time step.

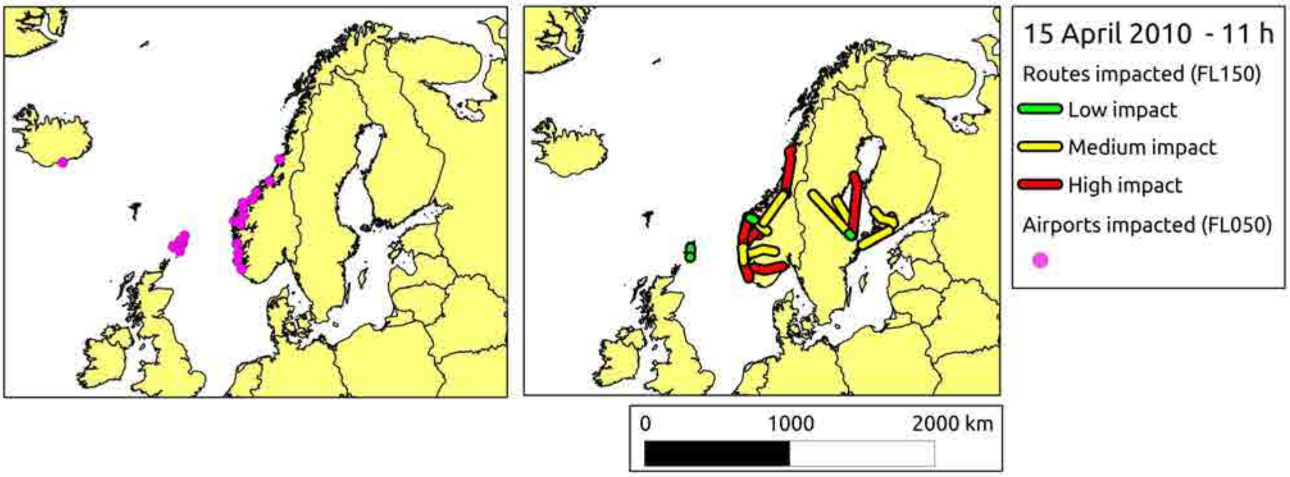

Fig. 2. Visualization of hourly impacts on European air traffic. The script exports graphical output in shp format, that can be visualized by any GIS system. The example shows airports impacted at FL050 (left) and routes impacted at FL150 (right), for 15^{th} April, from 11:00 UTC to 12:00 UTC at FL150. Impacted routes are visualized with green, yellow and red color, respectively for low, medium and high impact. Note that few flights were present at FL150, which is coherent with FL statistics (Fig. 1).

TABLE II
QUALITATIVE IMPACT CLASSIFICATION DEFINED FOR IMPACTED ROUTES, BASED ON THE PERCENTAGE OF ROUTE DISRUPTED.

Lenght disrupted x(%)	Impact	Impact rating	Strategy
x <10%	Low	1	Small deviation
10% <x <80%	Medium	2	Change FL
x >80%	High	3	Not flying

4) We select the segments that are intersected by ash cloud.
5) For each time step, we produce a table containing the characteristics of the whole flight (length, duration). We then calculate the disrupted length and consequently the percentage of the route that is impacted by ash.

Based on the impacted length, we distinguish three qualitative levels of impact: low (disrupted portion lower than 10%), medium (disrupted portion between 10% and 80%), and high (disrupted portion greater than 80%) (Table II). Criteria of 10% and 80% have been chosen according to our personal opinions and considerations, and can be changed. This criterion can be associated also with a limitation on impacted length in km, in order to include long distance and intercontinental flights. Finally, hypothesizing a constant speed of the aircraft, we estimate the exposure time.

V. RESULTS

We produced two hourly tables containing information on impacted airports and routes. As an example, Table III contains length and duration of disrupted flights, and the percentage of length impacted by ash cloud, value used to estimate the qualitative impact level. Results correspond to the 15^{th} April, from 11:00 UTC to 12:00 UTC at FL150. Having calculated the percentage length impacted by ash cloud, the corresponding impact level is assigned.

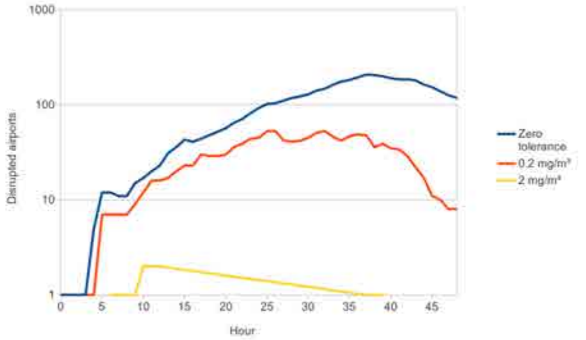

Fig. 3. Hourly impacts on airports for 15^{th} and 16^{th} April 2010 (48 hours) at FL050. The plot shows the number of impacted airports for the critical ash concentration threshold considered (zero tolerance, 0.2 and 2 mg/m^3). Note that the Y-Axis has logarithmic scale.

For every hour, we also produce a graphical output of the expected impacts. For example, Fig. 2 shows the impacts on airports (left) and routes (right) for 15^{th} April, from 11:00 to 12:00 UTC at FL050 for airports and FL150 for routes. Finally, we produce plots to summarize the impacts for the whole day or period. Fig. 3 summarizes impacts on airports, collecting all hourly information generated by the automated impact assessment methodology. We estimate the number of impacted airports for 15^{th} and 16^{th} April at FL050, relevant for take-off and landing operations, for the three critical thresholds of ash concentration considered. There is a peak in the number of impacted airports, considering the FL050, corresponding to

TABLE III
HOURLY IMPACTED ROUTES FOR 15^{th} APRIL, 11:00 TO 12:00 UTC. TABLE CONTAINS THE UNIQUE ROUTE ID, TOTAL AND DISRUPTED ("DIS") LENGTH AND DURATION (IN KM AND MINUTES, RESPECTIVELY), PERCENTAGE OF DISRUPTED LENGTH AND THE QUALITATIVE IMPACT RATING ASSOCIATED TO EACH FLIGHT (TABLE II)

Flight ID	Time tot (min)	Length tot (km)	Length dis (km)	Time dis (min)	Length dis (%)	Impact
135200495	33	247	221	29	89	3
135200372	34	268	252	32	94	3
135195266	268	974	172	47	18	2
135199465	57	582	343	34	59	2
135199991	38	436	334	29	77	2
135200164	48	545	327	28	60	2
135199526	40	425	280	26	66	2
135200166	68	782	257	22	33	2
135197704	141	656	139	30	22	2
135199822	66	697	74	7	11	2
135199382	73	605	65	8	11	2
135197704	141	646	54	12	8	1
135199866	36	251	17	2	7	1

approximately 15:00 UTC of 16^{th} April 2010.

Fig. 4 shows the hourly impacted routes for 15^{th} and 16^{th} April. Results have been produced for the critical thresholds at the considered FL (150, 200 and 250 from top to bottom). This figure allows visualizing the temporal evolution of impacts during the peak days of the emergency. Maximum impacts correspond to 16^{th} April, 04.00 pm and 15^{th} April, 13:00 and 07:00 UTC, respectively for FLs 150, 200 and 250. Highest disruptions are estimated at FL150 and FL200, while at FL250 only few flights would be highly impacted according to the analysis.

During the 2010 crisis, a high percentage of European flights were cancelled, as documented in the EUROCONTROL's Monthly Network Operations report for April 2010 [15], and the levels of European air traffic dramatically decreased due to the partial closure of European airspace (Table I). We compare the number of cancelled routes on 15^{th} and 16^{th} April 2010 [15] and the expected impacts resulting from our analysis for the zero tolerance criterion (Table IV). Table IV shows a high difference in the number of cancelled routes.

VI. DISCUSSION

The ultimate aim of this work is to support the decision-making process, taking the highest advantage of the modelling output and transferring the relevant information to decision-makers. The final decision on whether to fly or not is not addressed in this document, but we aim to support this decision with the highest amount of information available.

First, the methodology presented here takes into account the developments done by the modelling community. Given that Eyjafjallajökull eruption has been carefully studied and input parameters are relatively well constrained, modelling is expected to give reliable outputs. Moreover, although ash charts are provided by VAACs every 6 to 12 hours, modelling results can have a higher temporal resolution, *e.g.* on the order of 0.5-2 hours. A higher temporal resolution allows to transfer information to the stakeholders in a more dynamic way. In fact, by estimating impacts at each time-step (one hour in our study), the improvements achieved in the estimation of ash concentration could be transferred to the decision-makers with the highest possible temporal and spatial resolution. This is particularly true with the implementation of new cutting-edge techniques such as data-assimilation, which is a suitable and not-so-far-fetched achievement for the scientific community [16]. These techniques could increase the accuracy of results [5], [17].

Results for the Eyjafjallajökull case-study can be useful for two main reasons: evaluation of what occurred during 2010 eruption with an hourly-based analysis, and possible integration of this methodology within current strategies. Results produced for each time step (Table III) would provide a more dynamic and timely information basis for managing disruptions than is the case with 6-hour forecasts. The calculation of length of disrupted segments and elapsed travel time through ash cloud is of particular interest. In fact, if critical ash ingestion rate is defined, these parameters may be integrated in the impact assessment methodology. It should be stressed that this comparison performed in Table IV is biased by the fact that, in 2010, results of the forecast were different from the ones used in this study. Moreover, it has been stated that many flight cancellations were not directly caused by the presence of ash, but were the consequence of the airspace closures (based on the forecasted ash presence). For these reasons, although the 2010 aviation breakdown has been widely studied in recent years, it is not straightforward to compare what occurred with *a posteriori* analysis. However, this comparison underlines the order of magnitude of differences between the 2010 impacts and the ones expected today. The aim of this comparison is not to criticize the air traffic management during 2010 but to underline the enormous opportunities for improvement in this field.

Results of *a posteriori* numerical modelling performed by Folch et al. [17] show that at FLs 300, 350 and 400 there was no critical concentration of 2 or 0.2 mg/m^3. If follows that changing altitudes to the upper FLs would have been possible, at least for the aircraft with the necessary technical characteristics. For this reason, the strategy of changing FL seems suitable for long-lasting eruptions with low eruptive columns, for the flights that are able to take-off (climb/descent is not impeded by ash presence).

TABLE IV
COMPARISON OF TOTAL NUMBER OF CANCELLED ROUTES ON 15^{th}-16^{th} APRIL 2010 AND ESTIMATED NUMBER OF IMPACTED ROUTES IN THIS STUDY.

Day	2010	This study
15^{th} April	7736	170
16^{th} April	16938	208

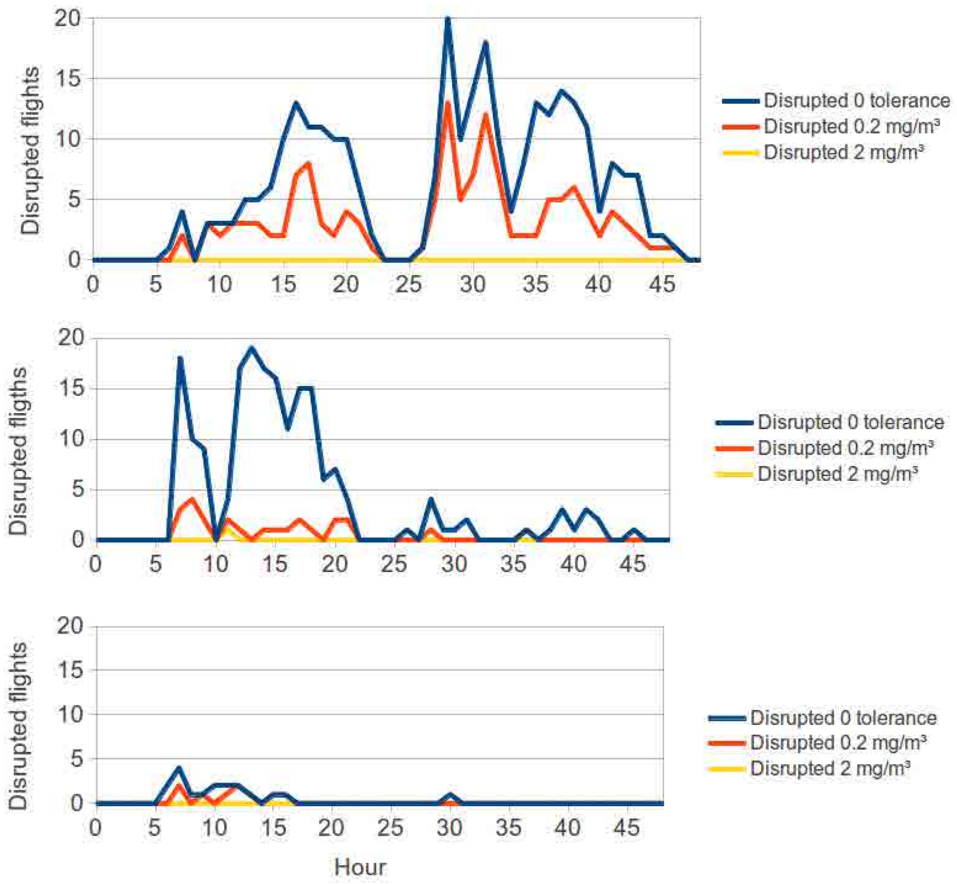

Fig. 4. Hourly impacts for 15^{th} and 16^{th} April 2010 for FL 150, 200 and 250 (from top to bottom). The plot shows the number of impacted routes for the critical ash concentration threshold in case of zero tolerance (blue) and for the thresholds of 0.2 and 2 mg/m^3 (red and yellow, respectively)

One important difference between the impact assessment methodology presented here and the one implemented within EVITA is that EVITA shows the effects for every 6 hours, while our methodology allows the estimation of impacts at every time step of the ash dispersal forecast. In addition, the operational automated forecast can be produced every few hours (depending on the resolution of the domain and the complexity of the eruptive scenario, but indicatively every 2-3 hours). This would allow to update the expected impacts with higher temporal frequency.

Both EVITA and the methodology presented here improve graphical outputs, compared with the initial tabular formats strongly criticized by several stakeholders [25], [27], [4]. In the case of EVITA, the graphical aspect received positive feedback during the VOLCEX exercises [4]. Our hourly maps are readable by GIS and Google Earth, which helps to better visualise results. Moreover, it supports the production of animations of the evolution of impacts. The use of these formats could also enhance the interoperability between different stakeholders and ultimately the communication and information management.

The methodology presented here is a first academic attempt to support civil aviation management in cases of ash-contaminated airspace. We are aware that this topic is very complex, and that we need to introduce improvements in order to produce a methodology that is flexible, adaptable and efficient. Table V synthesizes the main limitations and advantages of the methodology, as well as the possible improvements. On one hand, the impact assessment methodology relies on strong assumptions that greatly simplify the real processes, and is not operational yet. On the other hand, the main advantage of this methodology is that it links ash dispersal modelling and civil aviation management by providing the hourly results from the modelling output, which has a great practical value for decision makers, especially for the airlines, during the volcanic ash event. Further advantage is that this methodology can potentially be interfaced with results coming from any ash dispersal model, and is therefore model-independent.

TABLE V
MAIN LIMITATIONS AND ADVANTAGES OF THE METHODOLOGY. POSSIBLE IMPROVEMENTS ARE UNDERLINED FOR FUTURE WORK.

Limitations	Advantages	Improvements
Strong assumptions Not operational	Link science and management Synhtesis Hourly analysis Model-independent	Economic aspect Become operational Include probabilistic forecast

We identify three main roads for the future development of the presented methodology: including the economic analysis, interfacing this methodology with a probabilistic ash dispersal forecast, and integrating the methodology into a broader operational framework. First, the combined analysis of our results and the economic impact estimated for the 2010 crisis could help clarifying the process of propagation of impacts from civil aviation to society. Although the definition of economic impacts of civil aviation breakdowns is extremely difficult due to the multitude of variables involved, an effort should be made to include it in a broader multi-disciplinary methodology. Second, this methodology could have as input a probabilistic forecast, that is, a forecast constructed of many forecasts produced by varying the eruptive scenario. The ensemble of these forecasts would produce a probabilistic output, allowing to account for the uncertainties related to the modelling process. The probabilistic approach would strongly support new impact assessment methodologies.

Third, the GIS-based methodology presented here could also be integrated in the existing risk management strategies for civil aviation management such as VOLCEX exercises and SRAs. The implementation of the impact assessment methodology presented here, far from being straightforward, could enable the stakeholders to define operational strategies within their long-term plans, that would need to be supported by the input data (operational ash dispersal forecast and air traffic). Furthermore, the design of the reliable and user-friendly decision-support tool would greatly improve the usefulness of the methodology to the end users. Our contribution could therefore improve the current risk management strategies by supporting the decision-making process, in order to increase preparedness and eventually minimize losses.

VII. CONCLUSIONS

This work presents the first example of GIS-based ash dispersal impact assessment especially designed for civil aviation purposes. The impact assessment methodology presented here is a valid result in itself, and may be applied to other case-studies or implemented in a broader short-term risk management operational strategy. Specific results presented for Eyjafjallajökull 2010 eruption allow to perform *a posteriori* analysis of impacts and identify the critical issues to solve. Finally, this is a first attempt of filling a gap between ash dispersal modelling and civil aviation management, allowing to use the full potential of the model outcomes, and to produce practical results that can support an effective management of civil aviation during explosive volcanic eruptions.

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Appendix C

Web-based survey

Volcanic

Introduction

The ongoing research is focused on volcanic ash dispersal in atmosphere and its impacts on civil aviation. We are currently developing a map-based tool that allows estimating expected hourly impacts by an explosive volcanic eruption.

This survey aims at collecting the opinion of different stakeholders involved in civil aviation management during explosive volcanic eruptions. Understanding the opinion of stakeholders on ash dispersal models, temporal resolution, data management and output formats will improve the ongoing reserarch and be the the basis for further developments.

Survey is anonymous. The results of this survey are for scientific research purposes only. Please fill-in the survey only one time. Duplicate entries will be discarded. The survey takes aproximately 15 minutes.

Please, feel free to contact me at chiara.scaini@bsc.es for any question you may need for answering the survey.

Thank you very much for your time!

Volcanic

1- Personal

*1. Choose your area of expertise:

- ☐ Atmospheric modeling (e.g. ash dispersal modelers, meteorologists)
- ☐ Field and monitoring sciences (e.g. geologists, monitoring experts)
- ☐ Civil aviation management (e.g. public and private, international and national regulators and associations, airlines)
- ☐ Civil aviation employees (e.g. pilots, crew, controllers, CAA employees)
- ☐ Other stakeholder (e.g. services / activities connected to aviation)

Specify

2. How many years have you been working in each of these sectors?

Atmospheric modeling

Field and monitoring sciences

Civil aviation management

Civil aviation activities

Other activities

3. Where is your working experience based? (Multiple answers allowed)

- ☐ Europe
- ☐ Africa
- ☐ North-America
- ☐ South-America
- ☐ Asia
- ☐ Oceania

4. Check the box that corresponds to your age group:

- ○ < 30
- ○ > 30 and < 40
- ○ > 40 and < 50
- ○ > 50 and < 60
- ○ > 60

2 - Volcanic Ash Transport and Dispersal Models

***5. Are you familiar with the input of volcanic ash transport and dispersal models?**

- Yes
- No

Volcanic

***6. Are you an atmospheric modeler or field scientist?**

- Yes
- No

Volcanic

***7. Amongst the following list, choose the parameters that, in your opinion and to your knowledge, are used as input for volcanic ash transport and dispersal models (Multiple answers allowed).**

- ☐ Wind field
- ☐ Temperature
- ☐ Humidity
- ☐ Precipitation rate
- ☐ Column height
- ☐ Vertical mass distribution
- ☐ Mass eruption rate
- ☐ Total grain size distribution of particles
- ☐ Particle size
- ☐ Exit velocity
- ☐ Cloud height
- ☐ Ash concentration
- ☐ N/A

Other (specify)

Volcanic

***8. Here is a list of the input data commonly used by volcanic ash transport and dispersal models. Which is, in your opinion and to your knowledge, the level of uncertainty associated with these data?**

	Very low uncertainty	Low uncertainty	Medium uncertainty	High uncertainty	Very high uncertainty	N/A
Wind field	○	○	○	○	○	○
Temperature	○	○	○	○	○	○
Humidity	○	○	○	○	○	○
Precipitation rate	○	○	○	○	○	○
Column height	○	○	○	○	○	○
Vertical mass distribution	○	○	○	○	○	○
Mass eruption rate	○	○	○	○	○	○
Total grain size distribution of particles	○	○	○	○	○	○
Percentage of fine ash	○	○	○	○	○	○
Aggregation coefficient	○	○	○	○	○	○
Particle size	○	○	○	○	○	○
Exit velocity	○	○	○	○	○	○
Cloud height (satellite retrieval, for data assimilation)	○	○	○	○	○	○
Cloud load (satellite retrieval, for data assimilation)	○	○	○	○	○	○

Volcanic

***9. To which degree you think SO2 released by explosive vocanic eruptions in atmosphere can be hazardous for civil aviation?**

No impact	Very low impact	Low impact	Medium impact	High impact	Very high impact	N/A
○	○	○	○	○	○	○

***10. Are you familiar with the output of volcanic ash dispersal models (e.g volcanic ash cloud extent, ash concentration charts)?**

- ○ Yes
- ○ No

Volcanic

***11. Do you directly or indirectly use the outputs of ash dispersal models during explosive volcanic eruptions?**

- ○ Yes
- ○ No

Volcanic

12. For which purposes do you use outputs of volcanic ash dispersal models? (Multiple answers allowed)

- ☐ Emergency management
- ☐ Air quality assessment during explosive eruptions
- ☐ Civil aviation management during explosive eruptions
- ☐ Airline management
- ☐ Air quality management
- ☐ Long-term civil aviation management
- ☐ Long-term territorial planning
- ☐ Research

Other (specify)

13. Which output formats from ash dispersal models do you use? (Multiple answers allowed)

- ☐ NetCDF/HDF5
- ☐ Grib
- ☐ Other binary
- ☐ Text files (e.g. ASCII, txt, SIGMET, NOTAM)
- ☐ Ash concentration maps (e.g. pdf)
- ☐ Ash concentration maps, image format (e.g. jpeg, bmp, ps)
- ☐ Digital map (any raster or vector format)

Other (specify)

Volcanic

14. Which is your level of agreement with the introduction of a "standard output" (still under development) of volcanic ash dispersal models?

Strongly disagree	Disagree	Indifferent	Agree	Strongly agree	N/A
○	○	○	○	○	○

15. Do you think that the introduction of standart model output formats could enhance interoperability between VAACs?

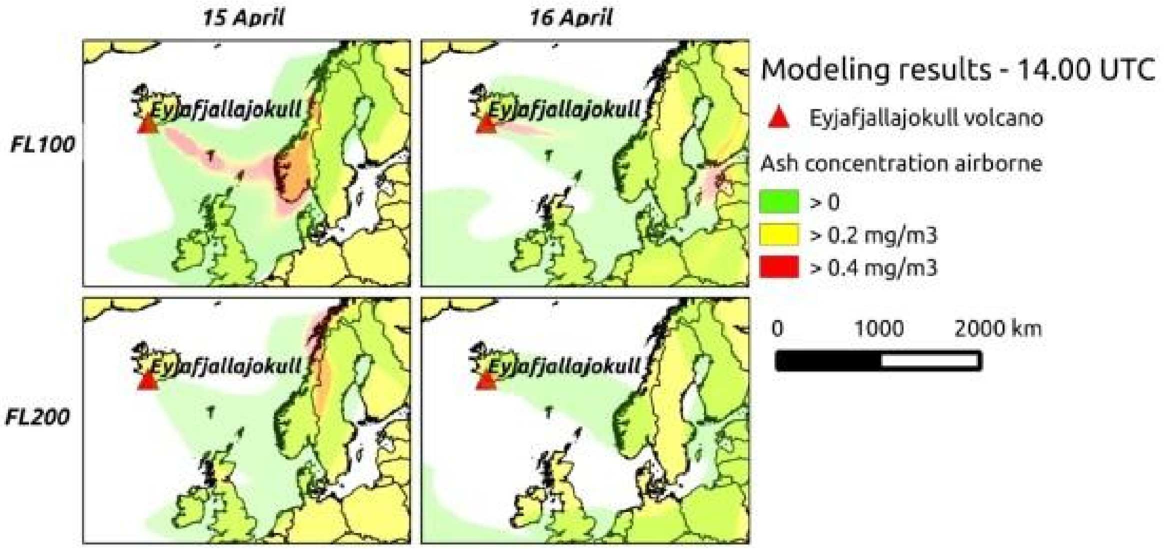
- ○ Yes
- ○ No
- ○ N/A

Volcanic

***16. Are you familiar with the graphical outputs of ash dispersal models presented in the figures below? Answer Y/N in the column "Familiar". Also, rate their usability for your work in the corresponding column.**

	Familiar	Usability
Raster image (Fig. 1)		
Cloud extent map (Fig 2)		
Cloud extent map in Google Earth (Fig. 3)		
Ash concentration curves (Fig. 4)		
Arrival time curves (Fig. 5)		
Residence time curves (Fig. 6)		
Probability curves for ash concentration (Fig. 7)		

FIgure 1 - Ash cloud extent (raster format)



Volcanic

Figure 2 - Map showing one contour for the extent of ash contamination at given concentration threshold and FL

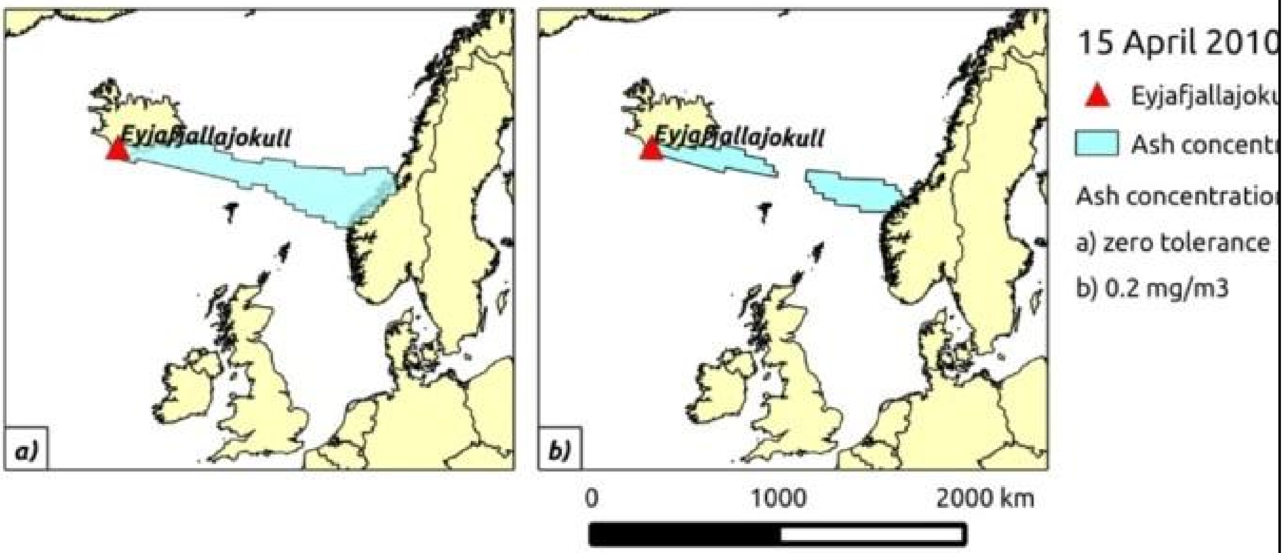


Figure 3 - Kml file of ash cloud extent

Volcanic

Figure 4 - Map with several contours for many ash concentration values

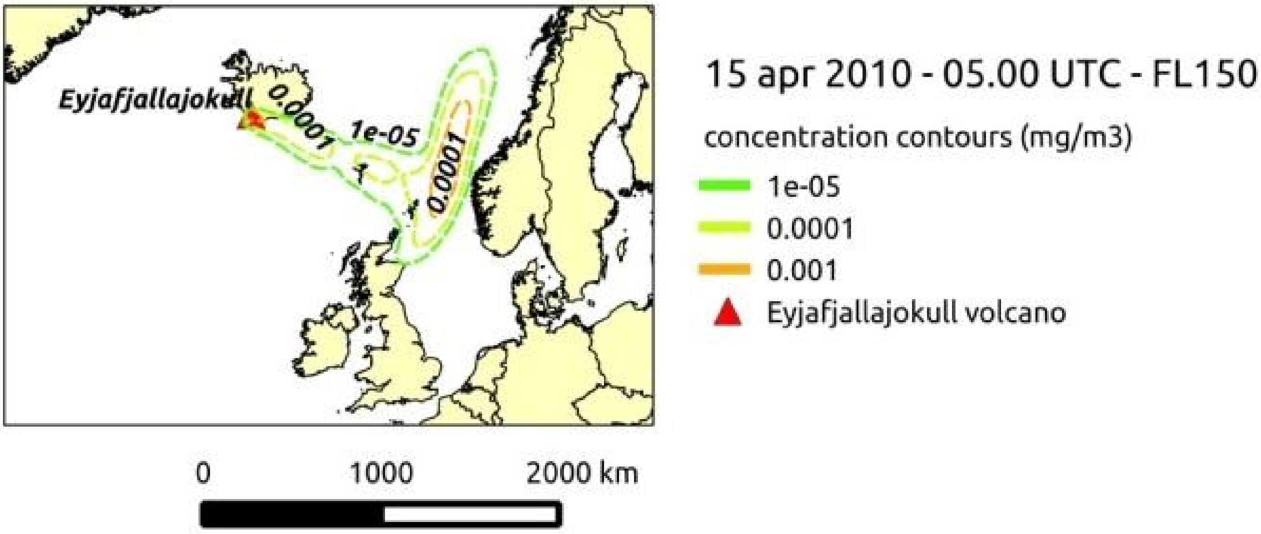
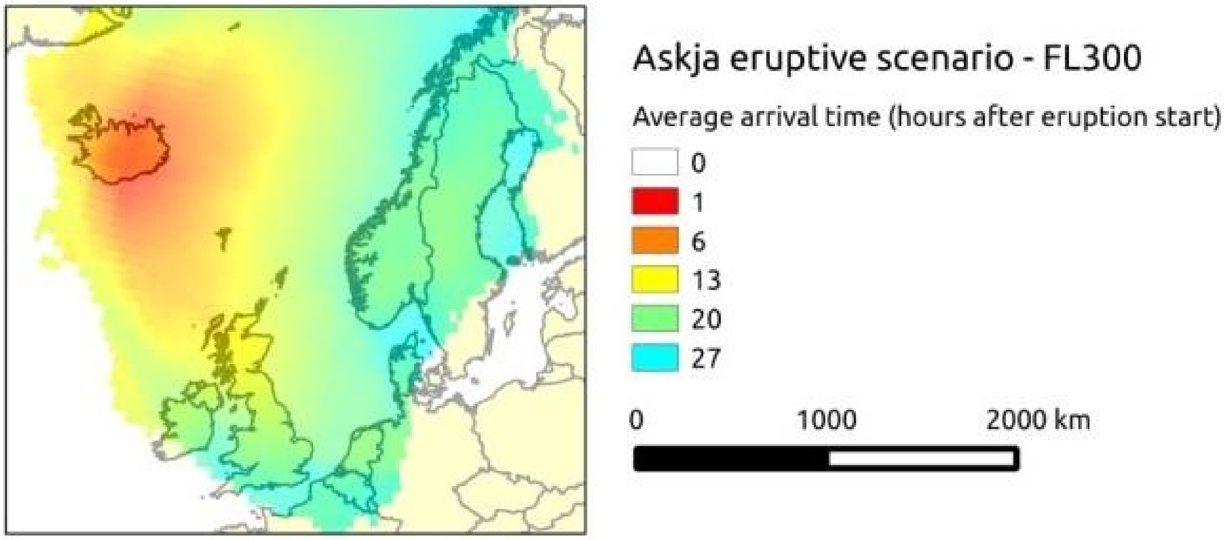


Figure 5 - Contours of arrival time for given ash concentration and FL



Volcanic

Figure 6 - Contours of residence times for given ash concentration and FL

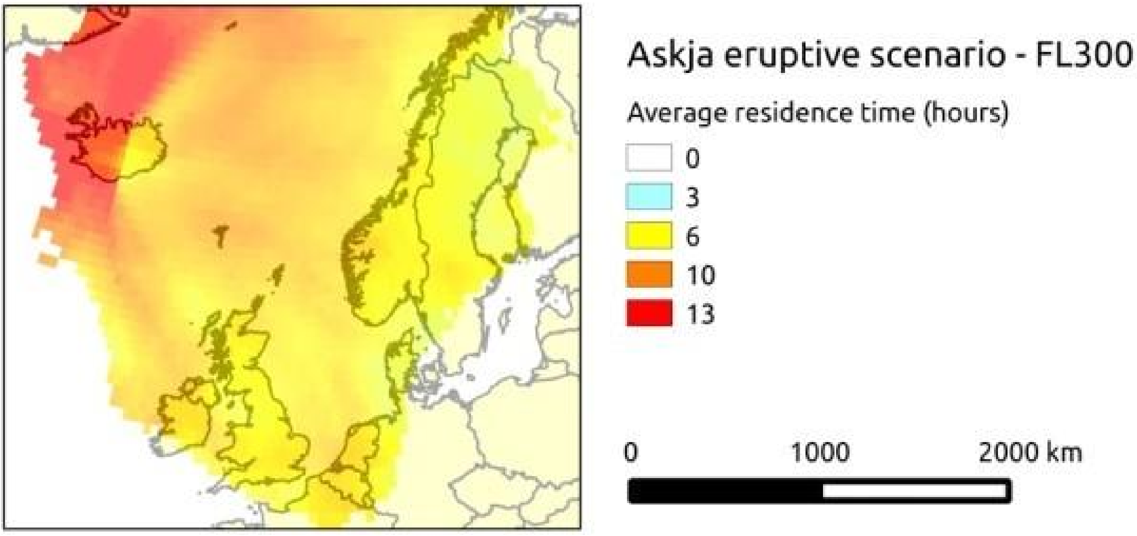
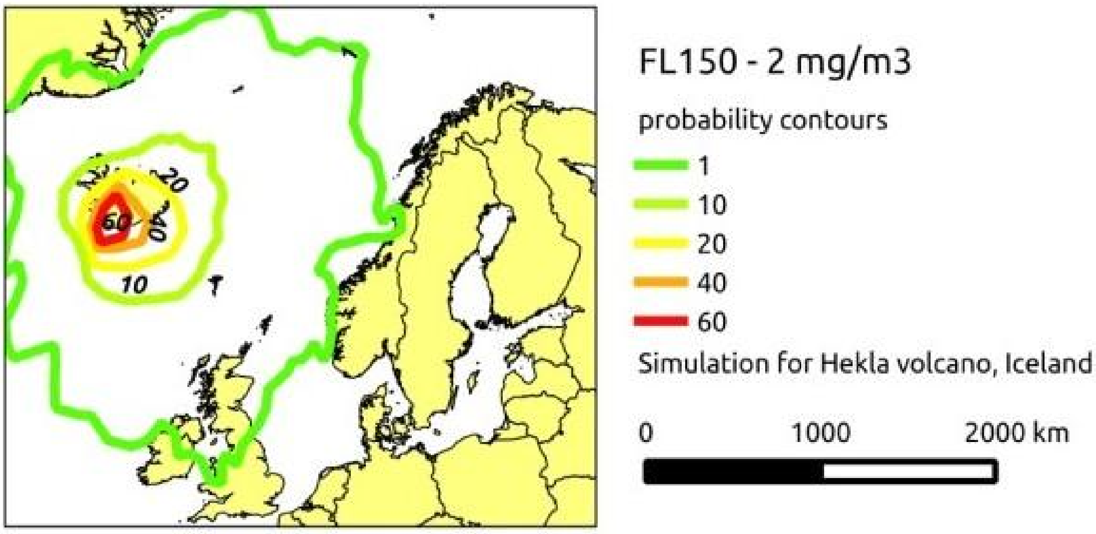


Figure 7 - Contours for probability of having ash concentration higher than a defined threshold, at a given FL. These maps are result of an ensemble modeling.



Volcanic

3- Ash concentration thresholds

***17. How much do you agree with the use of the following methods to define thresholds for allowing aircraft to fly or not into ash-contaminated airspaces? And how do your think each method is applicable (= it may be used operationally)? Express your opinion at a world-wide level and/or for the European area.**

	Agree - Worldwide	Applicability - Worldwide	Agree - Europe	Applicability - Europe
Zero tolerance				
Visible ash				
Discernible ash (discerned by satellite imagery and other indirect measures)				
Ash concentration based on forecast				
Ash concentration based on on-board instrumentation detection				
Engine rate (amount of ash ingested per unit of area, mg/m^2)				
Engine dose (engine rate for time unit, $mg/m^2 \cdot s$)				
Some combination of the above				

Other (specify)

4 - Temporal resolution

18. What does “short term” mean in your field of expertise? (Multiple answers allowed)

- ☐ < 10 minutes
- ☐ 10 minutes to 1 hour
- ☐ 1 to 24 hours
- ☐ 1 to 5 days
- ☐ 5 days to 1 month
- ☐ 1 month to 1 year
- ☐ > 1 year

Other (specify)

19. What does “long-term” mean in your field of expertise? (Multiple answers allowed)

- ☐ > 10 years
- ☐ 10 to 1 year
- ☐ 1 year to 1 months
- ☐ 1 month to 5 days
- ☐ 5 days to 24 hours
- ☐ 24 to 1 hour
- ☐ < 1 hour

Other (specify)

Volcanic

20. If an explosive volcanic eruption takes place, how often do you or your organization ISSUE information related to volcanic ash transport and dispersal in atmosphere? By information we mean all formats related to ash dispersal modeling in atmosphere: ash dispersal modeling outputs, VAA (Volcanic Ash Advisory), VAC (Volcanic Ash Chart), SIGMET (Significant Meteorological Information), NOTAM (Notice To Airman), etc.

- less than once a day
- every 24 to 12 hours
- every 12 to 6 hours
- every 6 to 1 hour
- every 1 hour to 10 minutes
- less than 10 minutes
- I do not issue information related to volcanic eruptions

Other (specify)

21. How often would you like to RECEIVE information related to volcanic ash transport and dispersal in atmosphere to perform your task? By information we mean all formats related to ash dispersal modeling in atmosphere: ash dispersal modeling outputs, VAA (Volcanic Ash Advisory), VAC (Volcanic Ash Chart), SIGMET (Significant Meteorological Information), NOTAM (Notice To Airman), etc. (Multiple answers allowed)

- every 24 to 12 hours
- every 12 to 6 hours
- every 6 to 1 hour
- < 1 hour
- I do not use/need information related to volcanic eruptions

Other (specify)

5 - Air traffic management during explosive volcanic eruptions

***22. Are you dealing with management in aviation in case of explosive volcanic eruptions?**

- Yes
- No

23. How useful is, in your experience, each of the data type listed below for air traffic management BEFORE explosive volcanic eruption take place?

	Useless	Of little use	Useful	Very useful	Extremely useful	N/A
Meteorological data	○	○	○	○	○	○
Volcanological data (expected eruptive scenarios)	○	○	○	○	○	○
Hazard assessment results (probabilistic hazard maps produced for expected eruptive scenarios)	○	○	○	○	○	○
Flight trajectories, flight plans similar data sources	○	○	○	○	○	○
Location of airports	○	○	○	○	○	○
Aircraft or engine type	○	○	○	○	○	○

Other (specify)

24. How useful is, in your experience, each of the data type listed below for air traffic management DURING an explosive volcanic eruption?

	Useless	Of little use	Useful	Very useful	Extremely useful	N/A
Total grain size distribution	○	○	○	○	○	○
Particle composition	○	○	○	○	○	○
Temporal series of column height	○	○	○	○	○	○
Meteorological data	○	○	○	○	○	○
Satellite imagery	○	○	○	○	○	○
Ash dispersal maps (modelling outputs)	○	○	○	○	○	○
Aircraft trajectory (constituted by a set of segments and way-points)	○	○	○	○	○	○
Scheduled flights, last filed flight plans or similar data source	○	○	○	○	○	○
Location of airports	○	○	○	○	○	○
Airport status (closed/open)	○	○	○	○	○	○
Airspace status (danger zones, open/closed airspace)	○	○	○	○	○	○
Data from on-board instrumentation	○	○	○	○	○	○
Aircraft or engine type	○	○	○	○	○	○

Other (specify)

6 - Use of GIS

***25. Are you familiar with GIS (Geographical Information Systems)?**

- ○ Yes
- ○ No

Volcanic

26. Please, answer Yes, No or N/A to the following questions:

	Yes	No	N/A
How often do you get in touch with digital maps (raster images, vectorial files)?			
Is anybody in your working environment using GIS?			
Is anybody in your working environment using raster images?			
Are you familiar with Database Management Systems?			
Are you familiar with spatial Database Management Systems?			
Do you think GIS may support your current work?			

27. Which is your level of agreement with these sentences?

	Strongly disagree	Disagree	Indifferent	Agree	Strongly agree	N/A
GIS is suitable for visualization and processing of 3D variables						
GIS is suitable for visualization and processing of time series						
GIS is suitable for visualization and processing of satellite images						
GIS allows automating spatial analysis operations						
GIS programs having a graphical interface (e.g. ArcGIS, QGIS) are easier to use						
Command-line based GiS programs (e.g.GRASS, GMT) are faster in performing spatial analysis tasks						
Command-line based GiS programs (e.g.GRASS, GMT) allow higher customization of functions						

Volcanic

7- Current research: impacts of volcanic ash dispersal on civil aviation

We are developing a tool to estimate the impacts produced by an explosive volcanic eruption on civil aviation (to be presented at the Third Sesar Innovation Days, 26-28 November 2013).

Inputs of the tool are volcanic ash dispersal forecasts and air traffic data. Given these data, the tool estimates hourly impacts expected (flights disrupted, airports closed).

***28. Our GIS-based tool allows to post-process the output of ash dispersal models and produce hourly maps of ash concentration. To which extent would the production of hourly maps of ash concentration be useful for your work?**

Not useful	Indifferent	Useful	Very useful	Extremely useful	N/A
○	○	○	○	○	○

***29. Our GIS-based tool estimates expected impacts for a temporal resolution of one hour, which may be increased depending on the user's needs. To which extent would the production of hourly impact maps be useful for your work?**

Not useful	Indifferent	Useful	Very useful	Extremely useful	N/A
○	○	○	○	○	○

30. If impacts were to be classified in a qualitative way, which kind of classification would you prefer?

- 2 classes (low - high)
- 3 classes (low – medium - high)
- 5 classes (very low – low – medium – high – very high)
- 7 classes (very low – low – low to medium – medium – medium to high – high - very high)
- None of these
- N/A

Other (specify)

31. if impacts were to be classified on qualitative way, which of these methods would you use to define an indicator of impact produced by volcanic ash contamination on a given flight? Multiple answers allowed)

- Flight distance through ash cloud (km)
- Flight time trough ash cloud (sec)
- Percentage of flight length through ash cloud
- Percentage of flight time through ash cloud

Other (specify)

Volcanic

***32. For each type of hourly result produced by the tool, estimate its usefulness for your work.**

	Not useful	Indifferent	Useful	Very useful	Extremely useful	N/A
Expected airports impacted	○	○	○	○	○	○
Expected routes disrupted (length)	○	○	○	○	○	○
Expected airspaces impacted (Flight Information Regions (FIR) and Upper Information Regions (UIR))	○	○	○	○	○	○

***33. For each output format produced by the tool and displayed below, rate its usability for your work**

	Not useful	Indifferent	Useful	Very useful	Extremely useful	N/A
Hourly table (Fig. 8)	○	○	○	○	○	○
Time series (Fig. 9)	○	○	○	○	○	○
GIS map (Fig. 10)	○	○	○	○	○	○
Google Earth (Fig. 11)	○	○	○	○	○	○

FIgure 8 - Example of hourly table produced by the GIS-based tool. Table contains disrupted flights ID, lenght and duration of disruption (respectively in km and minutes) and percentage of disruption on the total flight lenght. A qualitative impact classification is associated to the percentage of disruption. Similar tables can be produced for airports and FIRS.

Flight ID	Time tot (min)	Length tot (km)	Length dis (km)	Time dis (min)	Length dis (%)	Impact
135200495	33	247	221	29	89	3
135200372	34	268	252	32	94	3
135195266	268	974	172	47	18	2
135199465	57	582	343	34	59	2
135199991	38	436	334	29	77	2
135200164	48	545	327	28	60	2
135199526	40	425	280	26	66	2
135200166	68	782	257	22	33	2
135197704	141	656	139	30	22	2
135199822	66	697	74	7	11	2
135199382	73	605	65	8	11	2
135197704	141	646	54	12	8	1
135199866	36	251	17	2	7	1

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Figure 9 - Example of time series produced for 48-hours time interval. Plot shows hourly number of disrupted flights for given ash concentration thresholds and FL. Similar plots can be produced for airports and FIRS. Re

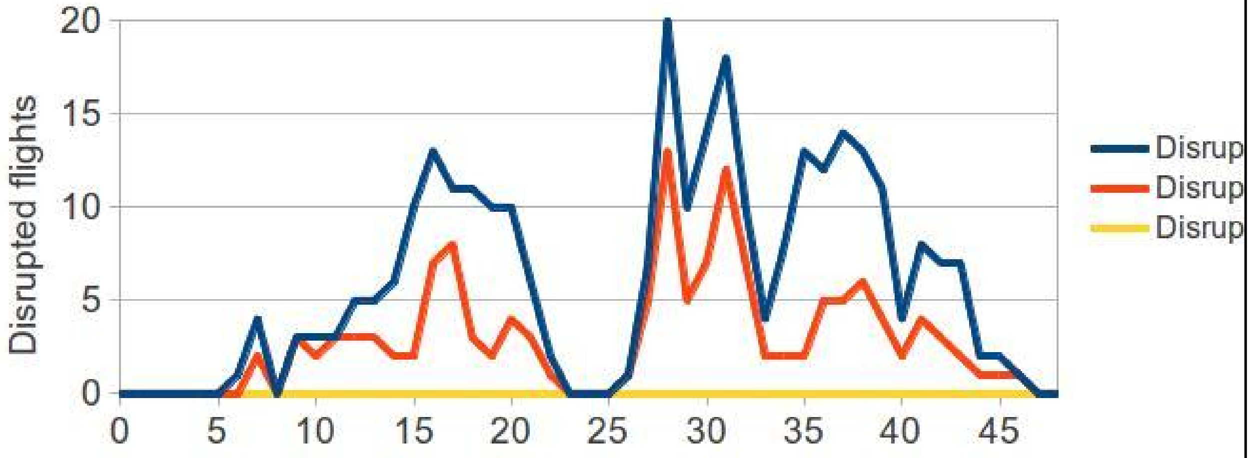

Figure 10 - Example of hourly GIS maps of disrupted airports (left) and flights (right). Disrupted flight segments are displayed in a colour-scale according to the impact assessment. Similar results can be produced for FIRS.

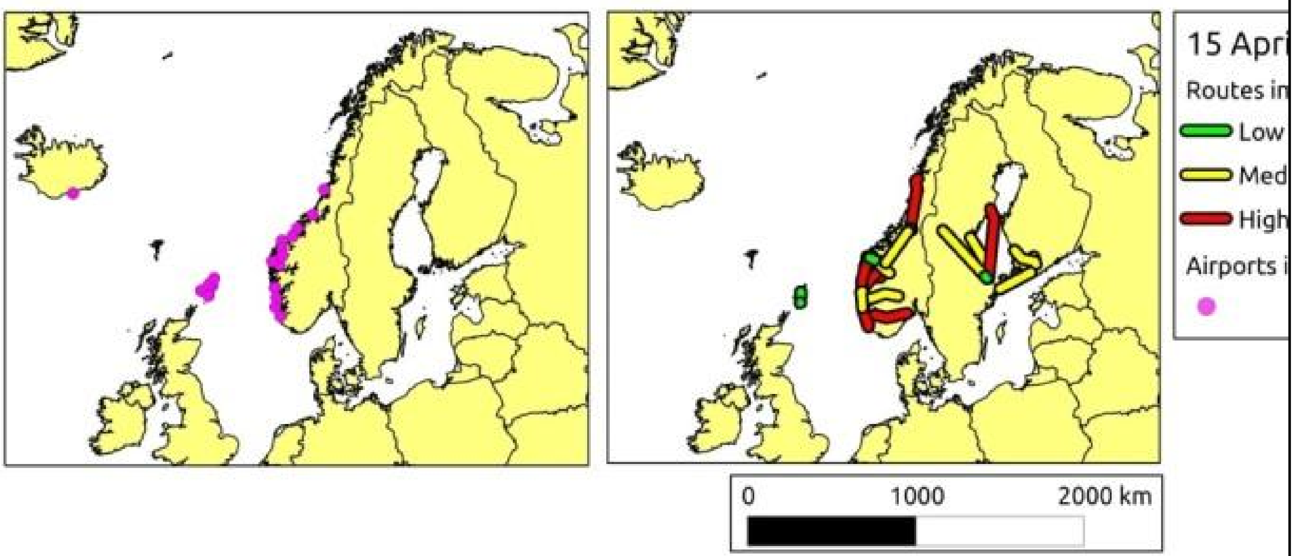

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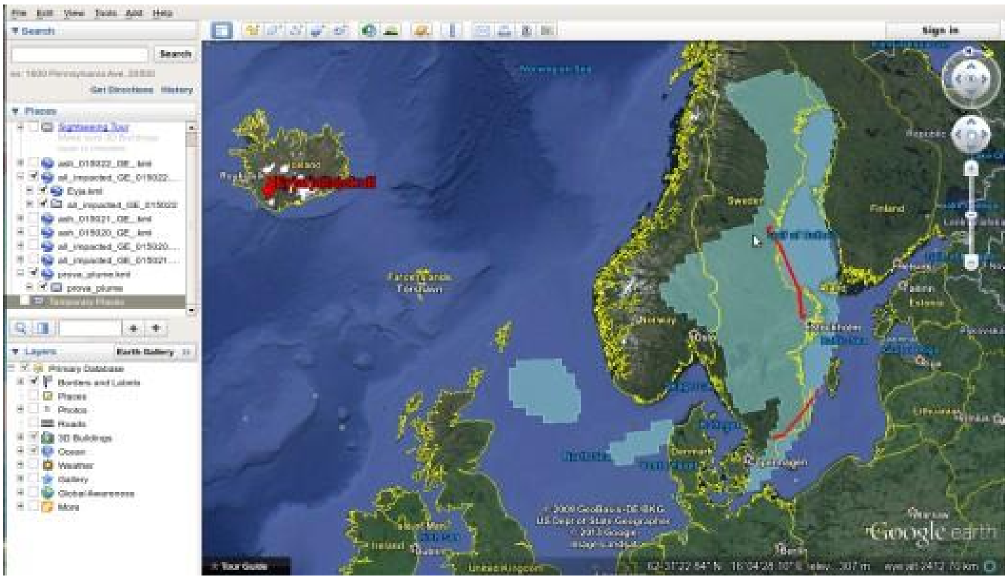
Figure 11 - Example of hourly KML map (visualized in Google Earth) of ash plume and impacted flights. The KML file contains basic information (flight ID, impact classification). Similar results can be produced for airports and FIRS.



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Our GIS-based tool (still under development) will allow user interaction. The user will be able to select parameters of impact assessment analysis, producing specific results (for example, impacts expected for a specific company and geographical area). The choice must be coherent with data availability and temporal and spatial resolution of tephra dispersal moodeling output.

***34. As a possible end-user of the impact assessment tool, would you like to select the input paramteters and produce specific results?**

- ○ Yes
- ○ No

35. Which parameters of impact assessment analysis would you select in order to produce specific results? (Multiple answer allowed).

- ☐ Ash concentration thresholds
- ☐ FLs
- ☐ Time frequency
- ☐ Time interval of the analysis
- ☐ Geographical area
- ☐ FIR
- ☐ Airline
- ☐ Airport selection
- ☐ Specific route
- ☐ City-pairs

Other (specify)

Volcanic

8 - Recent developments

36. Which are, in your opinion, the IMPACTS and the IMPROVEMENTS introduced by the procedures and techniques listed below (introduced or emphasized after 2010) on civil aviation management during volcanic eruptions? (By impact we mean the amount/relevance of changes induced).

	Impact	Improvement
Use of probabilistic eruptive scenarios based on event tree (methodology to define eruptive scenarios based on previous knowledge, experts judgments and statistical inference)		
Improvement of monitoring (ground-based or satellite)		
Development of opportunistic measurements (measurement flights performed during the eruption, close to the volcano or in distal areas with forecasted ash presence)		
Development of on-board instruments for particle detection and cloud avoidance		
Data assimilation		
Ensemble forecast (probabilistic)		
Safety Risk Assessment (Mandatory for airlines in order to fly through ash-contaminated airspace.)		
New aircraft maintenance protocols		
Crew specific training		
EVITA (Map-based tool developed by Eurocontrol to display information related to air traffic and volcanic ash dispersal. Activated in case of volcanic eruptions.)		
VOLCEX (Exercise organized twice a year by ICAO in order to improve preparedness of stakeholders involved in civil aviation management during volcanic eruptions.)		

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***37. Recent developments in volcanic risk management (event trees, bayesian expers systems) support the definition of a priori eruptive scenarios. Did you know about the possibility of producing a priori forecasts?**

- ○ Yes
- ○ No

Volcanic

38. How much do you agree with the following sentences?

	Totally disagree	Disagree	Indifferent	Agree	Totally agree	N/A
Uncertainties on ash concentration calculated by ash dispersal models decrease after the eruption onset, when input parameters are more known by monitoring and satellite observations.	◯	◯	◯	◯	◯	◯
Uncertainties related to a priori forecast are not acceptable with the current scientific and technical knowledge.	◯	◯	◯	◯	◯	◯
Uncertainties related to a priori forecast are acceptable only for very well-known and well-monitored volcanic systems.	◯	◯	◯	◯	◯	◯
Having an a priori forecast in the unrest phase improves preparedness.	◯	◯	◯	◯	◯	◯
Having an a priori forecast in the unrest phase could support air traffic management during unrest.	◯	◯	◯	◯	◯	◯
Having an a priori forecast during the unrest phase can be confusing for the stakeholders involved in air traffic maangement.	◯	◯	◯	◯	◯	◯

Volcanic

9 - Probabilistic framework

39. To which extent do you use probabilistic data while performing your task in the following situations? And to which extent would you use probabilistic data if they were available to you?

	USE	WOULD USE
In your daily work		
Before explosive volcanic eruptions		
During explosive volcanic eruptions		

40. In your area of expertise, which is the range that is commonly considered as "low" probability?

- ☐ < 0.001 %
- ☐ 0.001 to 0.01 %
- ☐ 0.01 to 0.1%
- ☐ 0.1 to 1%
- ☐ 1 to 10%
- ☐ > 10 %
- ☐ N/A

41. In your area of expertise, which is the range that is commonly considered as "high" probability?

- ☐ 0.001 to 0.01 %
- ☐ 0.01 to 0.1%
- ☐ 0.1 to 1%
- ☐ 1 to 10%
- ☐ 10 to 50 %
- ☐ 50 to 80 %
- ☐ > 80 %
- ☐ N/A

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42. Recent developments in ash dispersal modelling suggest that, in a near future, outcomes of ash dispersal models may be probabilistic. What does it mean to you? (Multiple answers allowed)

- ☐ Some inputs of ash dispersal models are probabilistic
- ☐ All inputs of ash dispersal models are probabilistic
- ☐ Uncertainty associated with inputs of ash dispersal models is taken into account
- ☐ Some outputs of ash dispersal models are probabilistic
- ☐ All outputs of ash dispersal models are probabilistic
- ☐ Deterministic results of many ash dispersal models are combined to obtain probabilistic results
- ☐ Uncertainty associated with results of ash dispersal models is taken into account
- ☐ N/A

Other (specify)

Volcanic

43. Which is your level of agreement with these sentences?

	Strongly disagree	Disagree	Indifferent	Agree	Strongly agree	N/A
Probabilistic framework allows accounting for model uncertainties	○	○	○	○	○	○
Deterministic approach is easier to understand	○	○	○	○	○	○
Probabilistic framework allows to account for expert opinions	○	○	○	○	○	○
Probabilistic framework reduces safety	○	○	○	○	○	○

*44. Which is your overall level of agreement with the introduction of probabilistic framework in your work?

Strongly disagree	Disagree	Indifferent	Agree	Strongly agree	N/A
○	○	○	○	○	○

10 - Sources of misunderstanding

***45. We have noticed that some commonly used terms in risk management have different meanings or connotation amongst the surveyed groups. Have you ever experienced it?**

- ○ Yes
- ○ No

46. Amongst the concepts listed below, which may be a source of misunderstanding while communicating with other group of stakeholders?

- ☐ Eruptive scenario
- ☐ Threshold
- ☐ Acceptable risk
- ☐ Forecast
- ☐ Safety
- ☐ Airworthiness
- ☐ Strategy
- ☐ Action
- ☐ Procedure
- ☐ Harmonization
- ☐ Timely
- ☐ Confidence
- ☐ Uncertainty

Other (specify)

Volcanic

12 - Feedback

47. Have you ever participated in a survey specifically designed for volcanic ash impacts on civil aviation?

- ○ Yes
- ○ No
- ○ N/A

***48. Do you think that the communication and information flow amongst different stakeholders inolved in air traffic management during explosive volcanic eruptions should be improved?**

- ○ Yes
- ○ No
- ○ N/A

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Thank you very much for your time!